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Jean-Marc A. Gandonou
University of Kentucky

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ABSTRACT OF DISSERTATION

Jean-Marc A. Gandonou

The Graduate School

University of Kentucky

2005

ESSAYS ON PRECISION AGRICULTURE TECHNOLOGY
ADOPTION AND RISK MANAGEMENT

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the College of Agriculture at the University of Kentucky

By
Jean-Marc A. Gandonou

Lexington, Kentucky

Director: Dr. Carl R. Dillon, Associate Professor of Agricultural Economics

Lexington, Kentucky

2005

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ABSTRACT OF DISSERTATION

ESSAYS ON PRECISION AGRICULTURE TECHNOLOGY ADOPTION AND RISK MANAGEMENT

Precision agriculture (PA) can be defined as a set of technologies that have helped propel agriculture into the computerized information-based world, and is designed to help farmers get greater control over the management of farm operations. Because of its potential to spatially reduce yield variability within the field through variable rate application of nutrients it is thought to be a production risk management instrument. Subsurface drip irrigation (SDI) is another production risk management technology that is generating interest from the farming community as a result of new technological improvements that facilitate equipment maintenance and reduces water consumption.

In the first article the production risk management potential of these two technologies was investigated both for each technology and for a combination of the two. Simulated yield data for corn, wheat and soybeans were obtained using EPIC, a crop growth simulation model. Mathematical programming techniques were used in a standard E-V framework to reproduce the production environment of a Kentucky commercial grain farmer in Henderson County. Results show that for risk averse farmers, the lowest

yield variability was obtained with the SDI technology. The highest profit level was obtained when the two technologies were combined.

Investment in two sets of equipments (PA and SDI) to maximize profitability and reduce risk could however expose many farm operations to financial risk. In the second article, a discrete stochastic sequential programming (DSSP) model was used to analyze the impact of PA and/or SDI equipment investment on the farm's liquidity and debt to asset ratio.

In the last article, the cotton sector in Benin, West Africa, was utilized to study the transferability of PA technology to a developing country. Properly introduced, precision agriculture (PA) technology could help farmers increase profitability, improve management practices, and reduce soil depletion. An improved production system could also help farmers better cope with the policy risk related to cotton production. Results from the two models show that PA is less profitable for the risk neutral farmer but more profitable for the risk averse one when compared to conventional production practices. The adoption of the new technology also has very little impact on the choice of crop rotation made by the farmer.

KEYWORDS: Precision agriculture (PA), irrigation, risk management, mathematical programming, Biophysical simulation.

ESSAYS ON PRECISION AGRICULTURE TECHNOLOGY
ADOPTION AND RISK MANAGEMENT

By

Jean-Marc A. Gandonou

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ACKNOWLEDGMENTS

I would like to express my profound gratitude and sincere appreciation to Dr. Carl Dillon for his invaluable contribution and direction. His academic guidance, dedication, and extreme patience made possible the successful completion of this dissertation. His knowledge, insightful comments and high standards were instrumental in helping develop my research skills. I am also thankful for his friendship. Next, I wish to express my deepest appreciation to the members of my dissertation committee, Dr. David Freshwater, Dr. Ronald Fleming, Dr. Scott Shearer, and Dr. Thomas Leinback for their invaluable comments, critiques, and advice that enriched this dissertation.

This dissertation would not have been feasible without the help and support of Dr. Wyatte Harman, Dr. Paul Dyke, Dr. Jimmy Williams, and Larry Francis from the Blackland Research Center in Temple, Texas. A special thanks to Dr. Harman who provided me with the training, database, and software necessary to generate my data.

I would also like to thank my fellow graduate students: Ibrahim Bamba, Agus Hudoyo, Murali Kanakasabai, Aksell Leiva, and Godfred Yeboah for their friendship and continuous encouragement.

Finally, my utmost thanks and appreciation to my wife Ching-Lun Gandonou for her love, endurance, understanding, and tireless support during those long years. Thanks also to our daughter Emma for being the driving force and motivation that allowed me to finish this work. A special thank also to my mom, Marie-Gisèle Degbey, for her unwavering support and sacrifices that made it possible for me to achieve my academic goals. Also thanks to brother Hellenick and my sister Dominique for their continuous moral support.

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Chapter 1 Introduction

"Through the ages agriculture production systems have benefited from the incorporation of technological advances primarily developed for other industries.

The industrial age brought mechanization and synthesized fertilizers, the technological age offered genetic engineering and now the information age brings the potential for Precision Agriculture" (p 1)

(Rasher, M).

Defining Precision Agriculture

Tailoring soil and crop management to match varying conditions (soil texture, moisture and nutrient status, seeding, etc.) within a field is not entirely new to farmers around the world. Small hold farmers in Asia, Africa or Europe using pre-industrial cropping practices are fully aware of spatial and temporal yield variability in both space and time, and change farm practices (e.g., seeding rates) depending on site conditions to optimize soil resources and external inputs. After the industrial revolution and the intensification of chemical fertilizer used on larger fields, the concept was temporally retired in industrial countries.

Today, technological progress in communication, along with the information revolution made possible the revival of such a concept, as well as its applicability on a larger scale. Precision agricultural technologies, such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing, yield monitors, and guidance systems for variable rate application, made it possible to manage within-field variation on large scales. The GPS is one of the key elements of PA and is used to determine the agricultural operator's exact geographic position in the field for operations

like field mapping, soil sampling, yield monitoring, or variable rate seed or nutrient application. The GIS is a software application that is designed to provide the tools to manipulate and display spatial data (Blackmore). It enables the farm operator to computerize maps, display and analyze diverse types of spatial data (soil types, ponds, fences, etc), land topography, or spatial variability of soil characteristics (N, P, K, pH, compaction, etc). Finally, sensing technologies can be used to obtain various layers of information about soil and crop conditions. These technologies allow detection and/or characterization of an object, series of objects, or the landscape without having the sensor in physical contact (Viacheslav et al.). Remote sensing uses aerial or satellite imaging to sense crop vegetation and identify crop stresses and injuries or pest infestation.

As an application of the new information technology adapted to agriculture, the essence of this technology is based upon the availability of data and the use of this data in the decision-making process (Lowenberg-DeBoer, 1997a). Data collected from soil sampling, yield monitoring, crop scouting, remote sensing, and satellite imaging are used to create maps. For example, yield map data can reveal a low yielding area. Remote sensing imaging techniques can highlight crop stress, disease and other field or crop characteristics. Many of these maps can be overlaid to look at interactions between yield and topography or yield and soil N content for example. It is the specific ability to process multiple layers of spatial data (yield maps, soil maps, or topography maps) that makes PA a powerful management and decision tool. The availability of historical data combined with multiple layers of information for a farmer engaged in PA improves the quality of inputs recommendations and management decisions. The effectiveness of the decision making however, will depend on a quick and accurate analysis of temporal and

spatial data. In this context, precision farming technologies are widely known to assist growers in making informed decisions. By helping in making informed management decisions, PA could be used by producers as an effective management and risk management tool.

Risk in Agriculture

Harwood et al. defined risk as “the possibility of adversity or loss, and referred to it as “uncertainty that matters” (p 7). Consequently, risk management involves choosing among alternatives to reduce the effects of risk. It typically requires the evaluation of tradeoffs between changes in risk, expected returns, entrepreneurial freedom, and other variables. From Bodie and Merton, risk is uncertainty that affects an individual’s welfare, and is often associated with adversity and loss.

According to a 1997 Iowa Farm and Rural Life Poll, 66 percent of producers think that risk in farming has been increasing (Lesley). Changes in the risk environment and the tools available to manage risk have resulted in an increased need for risk management skills among farmers and ranchers. Adoption of new technologies like precision agriculture could help farmers mitigate some categories of risk like production risk or individual risk. The PA technology was defined by Blackmore as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality. As such PA could be an effective production risk management tool given its ability to reduce the spatial variability of crops’ yields. Investigation of this assumption was one of the primary motivations behind this dissertation.

Another observation that motivated this research was the apparent disconnect between academic research on the profitability of PA and the low adoption rate by farmers. The precision agriculture profitability review conducted by Lambert and Lowenberg-DeBoer in 2000 found that 73 percent of the studies done on the profitability of PA concluded that adoption of the technology was profitable. In spite of these results, many surveys show that the adoption rate of the PA technology is still relatively slow in the United States (Dayton and Lowenberg-DeBoer). Many reasons have been offered to explain this discrepancy. Swinton and Lowenberg-DeBoer found that all the reported studies did not include all of the PA adoption cost such as training and information cost. They also raise questions about the profitability of phosphate, potassium, and nitrogen (NPK) particularly on bulk commodities. Bullock, et al. linked PA's slow rate of adoption to low profit potential and the high cost of the equipment. High equipment costs have also inhibited the adoption of PA on smaller farms (Popp and Griffin, Kastens). Though the initial cost could appear relatively small for many farmers compared to the cost of other farm equipment, the high total annual cost, primarily due to the short useful life of the equipment, could cause cash flow or debt load problems. Evaluation of the financial impact of the PA equipment cost on the farm's liquidity and debt load was another objective of this research.

Objectives

Given the unique characteristics and risk management potential of each of these two technologies, it was important to develop a full farm level model representing the production environment of a Kentucky grain farmer using either or both technologies. Recognizing that both profitability and production risk management are key factors

driving farm managers decision to adopt new technologies, a modeling framework was developed to help determine the driving force behind SDI adoption in Kentucky. Adoption of either of these two technologies could prove profitable or represent an excellent risk management tool, yet not be affordable by the farmer.

Investment in new production technologies like PA with uncertain profitability could disrupt the farm operation's financial stability. Two of the main obstacles to adoption often stated by farmers, are the initial investment cost and the uncertainty about profitability. Investment in either of these two production technologies could then be desirable, but not financially feasible. Therefore, it was important to develop an analytical tool that would examine the impact of an investment in either or both technologies on the farm financial indicators.

The primary objectives of this dissertation were to:

- 1) Develop a realistic modeling framework for the simultaneous adoption of precision agriculture and sub-surface drip irrigation in Kentucky;
- 2) Analyze the impact of the producer risk preference on profitability, production choices, and financial risk in the context of the above; and
- 3) Develop a framework for precision agriculture adoption and profitability in a developing country with consideration for environment.

Mathematical programming and risk management

Farmers' risk aversion levels and decision making under uncertainty have been modeled in the economic literature with different methods (Binswanger; Dillon and Scandizzo; Antle; Anderson et al.; Freund; Hardaker et al.). This study uses a mathematical programming model to "capture" the risk inherent in a farmer's decision-

making process. The technique used here is known as expected value variance (E-V) analysis and was first developed by Markowitz and Freund for its application in mathematical programming. It allows an analysis of the farmer's profit maximizing production strategies under different risk aversion levels. The risk parameter was incorporated in the objective function assuming that the parameter's probability distribution is known with certainty (Appendix 1). Mathematical programming risk models also have the capability to depict the risk inherent in model parameters. This methodology was used in all three articles.

In the second article, in addition to E-V, a second modeling methodology was introduced to model financial risk. The financial risk associated with the investment in either of the two technologies uses a discrete stochastic sequential programming (DSSP) model. With DSSP risk is embedded when decisions are made sequentially. Here, a three period investment decision model was developed to analyze the impact of price and interest rate risk on PA and/or SDI on investment decision and farm financial health. In the last article, a steady state crop rotation model was developed under a standard expected value variance (E-V) framework.

Dissertation outline

This dissertation's objectives, outlined above, were met in a three manuscript format. The first article examined the profitability of PA technology and irrigation as well as their potential to reduce the production risk faced by farmers. The analysis was done for each technology individually, but also examined the combined effect of the simultaneous adoption of both technologies. Finally, custom hiring PA services being a common practice in Kentucky, two different scenarios were analyzed: investment in the

PA equipment, and custom hiring of PA services. The example of a commercial grain producer in the Ohio Valley region of Kentucky was utilized.

In addition to the production risk analyzed in the first article, the second article expands on the analysis of the financial risk related to an investment in the new equipment. The emphasis in this second paper was to realistically model the production but also the financial constraints that the decision maker faces. Crop price and interest rate risk were modeled using a discrete stochastic sequential programming (DSSP) framework.

In the third article, the question of PA technology transfer to a developing country was examined. First, a framework for some components of PA technology adoption was proposed. Here, in addition to evaluating its profitability, the potential for PA to help Benin cotton farmers deal with existing environmental issues in a politically uncertain environment was also analyzed. Adoption of some components of precision agriculture technology could help improve current production practices, alleviate poverty by increasing profitability and, subsequently, enable farmers to better cope with a changing institutional environment.

Chapter 2 Precision Agriculture, Whole Field Farming and Irrigation Practices: A Production Risk Analysis

Introduction

Precision agriculture (PA) represents a significant evolution in agricultural production practices and has helped propel agriculture into the computerized information-based world. For Roberts, “PA is an information technology revolution made possible by new technologies” (p 2). Four key information technologies are currently used in PA: Global Positioning System (GPS), Geographic Information System (GIS), controller for variable rate application (VRA) of crop inputs, and sensing technologies (Swinton and Lowenberg-DeBoer, 2001). Because of the growing scope and areas of application offered by the technology, a definition of consensus is yet to be found. One of the broadest of the definitions offered to capture the PA concept was proposed by Lowenberg-DeBoer and Boehlje who defined it as “electronic monitoring and control applied to agriculture, including site specific application of inputs, timing of operations and monitoring of crops and employees” (p 923).

Site-specific application of inputs is only one of the components of PA technology. Site-specific in PA is a term that refers to the treatment of the smallest possible area as a single element (Pfister). A site is a unit a farmer can manage individually and can be a grid within a field or an individual plant. Narrowing the concept to its site-specific component, Blackmore defines PA as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management corresponding to the unique conditions found in each field while maintaining environmental quality. This latter description will be used in the remained of this dissertation to define PA. Precision

agriculture therein enables the farm operator to spatially micro-manage each section of the field according to its specific characteristics. Only the variable rate application (VRA) of fertilizer was considered in this study. As such, PA has the potential to reduce the spatial distribution of yield across the field and is often perceived as a yield risk management tool (Lowenberg-DeBoer, 1999).

Managing yield risk has always been a challenge for farmers and farm managers. They can have the best of prices but, if they have little or nothing to sell, the results can be disastrous. Production or yield risk results from various factors, such as weather related events (insufficient rainfall, hail, etc), insects, diseases, crop variety choice, soil characteristics, or production techniques. Here, only soil and weather related components of yield risk will be modeled. Precision Agriculture could enable the producer to manage the spatial component of the yield risk s/he is exposed to but does not always help her/him deal with weather risk. A study by Braga et al. evaluated the ability of PA to reduce weather risk impact on yield. They found that higher grain yields were achieved during better weather years for similar nitrogen (N) application rates. However, combining soil types and weather years did not increase the accuracy of the scenarios studied. They concluded that PA did not reduce risks associated with weather.

Irrigation is a traditional and capital-intensive weather and yield risk management technology (Bogges and Amerling, Yee and Ferguson, Hatch et al.). It was therefore expected that the combination of PA and irrigation would have the potential to substantially reduce the yield risk faced by producers. The primary objective of this paper was to understand the driving forces behind the increased adoption of the sub-surface drip (SDI) and center pitot (CP) irrigation systems in Kentucky, and the slower adoption

of PA. A mathematical programming model was developed to replicate the production conditions of the commercial grain (corn, wheat and soybeans) producer. The producer had the option to produce under conventional, precision agriculture and/or irrigation practices. The three main elements analyzed were the profitability of each production practice (or a combination of two practices), the optimum crop mix obtained for the specific production practice as well as the associated risk management potential. The example of a commercial grain producer in the Ohio Valley region of Kentucky was utilized. The producer was given the option to purchase the PA equipment or custom hire the service.

This paper contributes to the agricultural economic literature in general and to the PA literature in particular in many ways. It is the first comprehensible research that uses soil specific historical simulated crop yield data to model the profitability of PA and its impact on production risk management. By comparing PA to another production risk reducing technology, subsurface drip irrigation (SDI), it puts into perspective the relative importance of PA as a risk reducing technology.

The paper was organized as follows. In the first section, an overview of some of the issues related to irrigation in Kentucky, and precision agriculture and risk management were presented. Then an overview of the mathematical programming method used to model risk was provided, followed by a description of the empirical model. Finally, the data included in the model as well as the methodology used to obtain these data were described, followed by a discussion of the results, and the conclusion.

Background

Irrigation in Kentucky

Use of irrigation in Kentucky has historically been very limited. The state's geology limits the quantity of ground water available for irrigation water needs for most farmers. Kentucky also benefits from sufficient rainfall with a mean annual precipitation total of 45 inches. Rainfall can, however, be unevenly distributed during the growing season. On average, the proportion on irrigated land continues to decrease in Kentucky. According to the 1997 and 2002 Kentucky census data, the proportion of harvested irrigated cropland in Kentucky decreased from 1.16 percent in 1997, to 0.74 percent of total harvested land in 2002. Total harvested cropland increased from 4,853,500 acres in 1997 to 4,978,994 in 2002 while harvested irrigated land decreased from 56,366 acres to 36,718 in the same period.

Compared to most Counties in Kentucky, irrigation is relatively important in Henderson County and continues to gain ground. Total irrigated harvested land increased by 55 percent from 1992 to 1997, and 24 percent from 1997 to 2002 (2002 census data). While the total harvested cropland was decreasing in the county, irrigated land was increasing. In 1997, irrigated land represented 11 percent of total harvested land, and 14.6 percent in 2002.

Though center pivot remains the main irrigation technique used in the County, there was an observed trend toward an increased adoption of subsurface drip irrigation (SDI). Subsurface drip irrigation is an irrigation system that applies water directly to the root. It is a relatively old irrigation system that benefited from substantial technological improvement during the last 20 years (Camp et al.). The improvement in the system's

reliability and longevity made it more and more relevant and profitable for bulk crop producers. For Kentucky farmers, SDI presents multiple advantages. First, the high efficiency level of the system (over 90 percent) results in a reported irrigation water requirement as much as 40 percent less than for other irrigation methods (Camp et al.). Second, the flexibility of the system design makes it particularly suitable to Kentucky's sloppy landscape. Technical improvement and increased durability make it also accessible to Kentucky bulk crop growers given that the investment cost can be spread over a longer period. According to the author's knowledge, there are only a few studies related to the profitability of irrigation in Kentucky.

The profitability of irrigation practice used in Kentucky has not clearly been established. Two studies on corn and soybeans have shown that irrigation could be profitable in KY in the long run. Irrigation research in Kentucky indicates that irrigation investment could be profitable for field crops (Murdock). Herbek however, in his analysis of irrigated soybeans concluded that it is difficult to determine whether an irrigation system used only for soybeans would be economically profitable. He suggested that, if irrigation was used for other crops such as corn, soybean irrigation would appear more feasible since the investment would be spread over several crops. None of the studies, however specified the type of irrigation system used in the analysis.

Precision agriculture and risk management.

The development of precision agriculture technology was made possible in the early 80's by the new information technology revolution and the development of the Geographic Information System (GIS). The GIS made it possible to geographically manage different areas of the field according to their unique condition and characteristics.

For some in the literature, precision agriculture is a concept. For others, it is a philosophy. For producers, it is certainly a management strategy that matches resource applications and agronomic practices with soil properties and crop requirements as they vary across a site. An increasing control over the production process can be perceived as a mean to manage risk. Today, precision agriculture (PA) is a technology that enables farmers to increasingly integrate and take control of the production process in order to improve the profitability of the farm operation and reduce production risk.

Many studies have evaluated the profitability of precision agriculture (see survey by Lambert and Lowenberg-DeBoer; Swinton and Lowenberg-DeBoer, 1998), but few have devoted attention to the risk reducing capability of precision agriculture. Research related to precision agriculture and production risk management differs in the type of risk that is measured, and in methodology. Griffin et al. used an enterprise budgeting technique to determine the profitability of PA and found no evidence to support the perception that PA reduces yield risk. The authors were unable to come to a definitive conclusion due in part to the lack of historical data and its limitation to a single case farm study. The authors also noted the inherent difficulties in evaluating the economic potential of precision farming with on-farm data. Lowenberg and Aghib, on the other hand, found evidence that site-specific management (SSM) reduces production risk. They used six farms' yield data over a three year period and three production practices: whole field management, variable rate fertilizer application based on soil type and grid soil testing. Mean-variance and stochastic dominance rule were used to analyze risk. Using the mean-variance decision rule along with sensitivity tests, they found that the soil type treatment consistently dominated the other two PA experiments for a risk averse decision maker. It

had both a higher average net return and lower variance. Finally, Oriade and Popp used a quadratic risk programming approach to evaluate the impact of PA on production risk. They found no evidence to support the assumption that the use of the PA technology reduced production risk. However, a typical production environment of a precision agriculture technology user, based on soil characteristics and variable rate application of fertilizer was not modeled in the study. Rather, a simplifying assumption based on average yield increase and custom precision farming fees, was used represent the PA technology. The conclusions derived from the research cited above about the potential of PA to reduce risk were limited by the lack of reliable historical production data.

Mathematical Programming Model

Model Background

In this study, a quadratic risk programming model was used to depict the production environment of a hypothetical Henderson County, Kentucky grain farmer producing corn, soybeans and wheat. S/he could choose to use precision agriculture technology (variable rate application of fertilizer), conventional technology (uniform rate application of fertilizer), or produce under irrigated or dry land conditions. The Erosion-Productivity Impact Calculator (EPIC), a crop growth simulation model, was used to generate the necessary yield data for each production strategy. It was hypothesized that the ability to control water application and variably apply fertilizer should give the producer much more control over his/her production environment and may represent an effective means to managing production risk. The model allowed PA and/or irrigation to be applied on selected areas of the field. The precision agriculture equipment could also be purchased or the operation could be custom hired. It was assumed that the farmer's

objective was to maximize expected utility. One of the unique contributions of this study was the analysis of the interaction between PA and irrigation. An evaluation of the impact of each production practice (or a combination of production practices) on profitability and production risk management was performed using historical simulated yield data.

Expected Value Variance (E-V) Framework

The current study relies upon the expected utility framework (Appendix 1) to analyze the production risks included in the objective function. The technique used here is known as expected value variance (E-V) analysis and was first developed by Markowitz for its application in mathematical programming. It allows an analysis of the farmer's profit maximizing production strategies under different risk aversion levels. In that framework, the farmer is left to choose the enterprise combination and level of production based on his own preference, his own introspective risk aversion (Scott and Baker). Though sometimes criticized in the past, it has been shown to be consistent with the expected utility theory (Freund, Meyer, Markowitz, Tobin). It was assumed that the decision maker maximizes expected utility and that the utility function is quadratic with respect to expected income and variance of income. Risk is measured in terms of variance of crop (or enterprise) net income. If three enterprises fall on the same mean-variance (E-V) frontier, then they are all efficient in an E-V sense, and all three producers could be rational in the sense that they maximize utility. It is accepted that the expected income is a decreasing function of the risk aversion level. That is, the more risk averse the farmer is, the lower his/her expected income will be. An empirical description of the model is presented in the following section.

Model formulation

This section describes the mathematical programming model that was used to replicate the production environment of a hypothetical Henderson County commercial grain producer. Henderson County ranks second in Kentucky for the production of corn and soybeans, and common production practices were herein modeled. Production risk was incorporated through a quadratic programming risk-aversion model. In this hypothetical farm, corn, soybeans and wheat were produced on a 547 ha (1350 acres) land area. Three possible production practices, conventional, variable rate nutrient (N and P) application, and irrigation were available to the producer. S/he could choose any combination that maximizes the farm's net return. Subsurface drip irrigation was chosen for the experiment. Irrigation in the crop growth simulation model was applied uniformly on the field; therefore, precision irrigation was not modeled.

In this model, the producer's objective was to maximize his/her expected average income (\bar{Y}) less the Pratt risk-aversion coefficient (Φ) times the variance of the total income, (σ_Y^2) for the risk averse farmer. The Pratt risk-aversion coefficient is a measure of the hypothetical producer's risk aversion, and was measured using the McCarl and Bessler method. The resultant general formula for calculating the risk aversion parameter is

$$\Phi = 2Z_\alpha/S_Y$$

where Φ is the risk-aversion coefficient, Z_α the standardized normal Z value of α level of significance, and S_Y the relevant standard deviation; the risk-neutral profit maximizing base case for each (Dillon). Total income here was defined as the expected annual return above selected variable cost.

$$\text{Max } \bar{Y} - \Phi \sigma_Y^2$$

To maximize the expected net return above variable cost, the producer had to allocate a limited amount of land resource endowment (ACRELIM_S , where “s” is the soil type) across various production parameters. The decision variable in the model was $\text{ACRES}_{C,P,F,D,S}$, the amount of land (or number of acres), allocated to each crop or enterprise (E), technology or production strategy (P), for a given soil type (S), fertilizer level (F), and planting date (D). The resulting land constraint equation was,

$$(1) \quad \sum_C \sum_P \sum_F \sum_D \text{ACRES}_{C,P,F,D,S} \leq \text{ACRELIM}_S \quad \forall S$$

and specifies that the area of land under production is less than or equal to the total land available. The land availability equation sets a constraint on the total land in production.

Similarly, a constraint was set on the quantity of fertilizer purchased. Only the exact quantity of inputs actually used will be purchased by inputs type (I). Equation (2) represents the constraint on total inputs (crop, fertilizer and technology cost) used.

$$(2) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{IREQ}_{I,P,F} * \text{ACRES}_{C,P,F,D,S} - \sum_I \text{IPURCH}_I \leq 0$$

Given that the model included a double crop soybeans and wheat rotation, constraint (3) was included to control for soybeans and wheat feasible planting sequences to prevent overlapping of planting dates. For example, early planting of double crop soybeans cannot follow late wheat planting. SEQ_D is a binary matrix, and “D” includes wheat and double crop planting dates. In that constraint “PS” and “PW” represent, respectively, soybeans and wheat planting dates, and “W” and “S” represent wheat and soybeans. Equation (4) is the rotation equation

$$(3) \quad \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"W"}, P, F, D, S}$$

$$- \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"S"}, P, F, D, S} \leq 0$$

$$(4) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{ACRES}_{\text{"C"}, P, F, D, S} - \text{ACRES}_{\text{"B"}, P, F, D, S} - \text{ACRES}_{\text{"W"}, P, F, D, S} \leq 0$$

To fully control for uniform and proportional fertilizer application across all soils, two control equations were included in the model. Equations (5a) and (5b) are ratio constraints to control for uniform (5a) and variable rate (5b) fertilizer application.

$$(5a) \quad \text{ACRELIM}_{S'} * \text{ACRE}_{D, F, S, P} - \text{ACRELIM}_S * \text{ACRE}_{D, F, S', P} = 0$$

$$\forall P = \text{URA}, F, D, S \neq S'$$

$$(5b) \quad \text{ACRELIM}_{S'} * \sum_E \text{ACRE}_{D, F, S, P} - \text{ACRELIM}_S * \sum_E \text{ACRE}_{D, F, S', P} = 0$$

$$\forall P = \text{VRA}, F, D, S \neq S'$$

On the output side, the model assumes that the entire production was sold after harvest. For a given year (N) and a given enterprise (E), the expected yield ($\text{YLD}_{E, N, D, S, P, F}$) was a function of the planting date (D), soil type (S), production strategy (P), and fertilizer application rate (F). The sales balance equation (6) states that the farmer cannot sell more than s/he produces. As a result, revenue or net income (Y_N) equals total sales minus total cost. Equation (7) represents the annual profit balance.

$$(6) \quad \sum_S \sum_P \sum_F \sum_D \text{YLD}_{E, N, D, S, P, F} * \text{ACRES}_{E, P, F, D, S} - \text{SALES}_{E, N} \leq 0 \quad \forall E, N$$

$$(7) \quad \sum_C P_C * \text{SALES}_{E, N} - \sum_I IP_I * \text{IPURCH}_I = Y_N \quad \forall N$$

Finally, the farmer's objective was to maximize the expected net return. The expected profit is the average net return over the simulation period (N=30). The expected profit balance equation (8) is:

$$(8) \quad \sum_N 1/N * Y_N = \bar{Y}$$

Indices include:

- E represents the enterprises (corn, wheat, full season or double crop soybeans)
- P is the production strategy (irrigated or dry land, variable rate application (VRA) or uniform rate application (URA) of fertilizer)
- S represents the different soil types (Grenada, Huntington, Loring, Memphis, and Wakeland)
- F is the fertilizer application level (very low, low, medium, high, and very high)
- D represents the planting dates for corn "PC", soybeans "PS", and wheat "PW"
- N is the number of years or states of nature

Activities include:

- Y_N is the expected net return above variable cost (across years)
- $ACRES_{EDSPF}$ is the number of acres produced for enterprise E on planting date D, soil S under production strategy P at fertilizer level F
- $SALES_N$ is the total farm sale in year N (in bushels)
- $IPURCH_I$ is the purchase of inputs I

Coefficients include:

- Φ is the Pratt risk-aversion coefficient
- IP_I is the inputs (I) price
- P_C is the price of crop E in dollars per bushel including related costs

$ACRELIM_S$	is the total number of acres available to the farmer by soil type S
YLD_{NDSPF}	is the expected yield during year N for enterprise E at planting date D, under production strategy P, on soil type F (in bushels per acre)
$IREQ_{IPF}$	is the inputs I required by production strategy and fertilizer level.

Model data

The model was solved using the General Algebraic Model Solution (GAMS) software. Data required to run the model as well as the methodology used to obtain them are described in the following section. The choice for using a crop growth simulation model is first explained, and characteristics of the model discussed. The model calibration and validation procedures are then described. Finally, other data used both in the crop growth and the mathematical programming will be described.

Biophysical model calibration and validation

Obtaining the necessary yield data for the mathematical programming model required using a biophysical simulation model. While such models are subject to criticism in the literature (Swinton and Lowenberg-DeBoer, 1998), they also certainly present great advantages particularly in the area of production risk management. With actual historical data, technology change provides a source of variation in output, which must be separated from variations due to risk influences (Musser et al.). Simulation models virtually eliminate the technology factor as a single technology is used over the modeling period. The data required for modeling production risk in the current mathematical programming framework makes it quasi-inevitable to use simulated data due to the unavailability of observed data. The biophysical simulation model used here has been proven in the literature to be both accurate and reliable (Appendix 2).

The EPIC model (Williams et al. 1984) was originally developed in 1981 to conduct a national survey of U.S. agricultural land and determine the relationship between soil erosion and soil productivity throughout the U.S.A. The components of the model include crop growth model, hydrology, weather, erosion, nutrients, soil temperature, tillage, or plant environment control. EPIC was tested and validated in a number of studies (e.g. Williams and Renard; Bryant et al., Watkins et al.).

In this study, EPIC was calibrated to replicate the production environment in Henderson County, Kentucky. County level historical daily weather and soil database were used for the simulation. Weather and soil databases were made available by the Blackland Extension and Research Center in Temple, TX. The center has a database of state soil and weather data in a format compatible with SWAN (Soil-Water-Air-Nutrients). SWAN is the EPIC windows interface used for this research.

The primary objective of the calibration process was to ensure that the yields generated by the model were not significantly too high or too low compared to the county's average yield, for example. Two components of the model, heat units and maximum annual irrigation water applied, were adjusted for each crop in order to replicate Kentucky weather conditions. Heat units (thermal time) were used to estimate the rate of crop development, and the fraction of crop maturity in a specific day was expressed as the number of heat units that had been accumulated up to that day divided by the number of heat units required for crop maturity (Mitchell, et al.). Maximum available water also needed to be adjusted and was limited to the average rainfall level in Kentucky. After the calibration stage, the model needed to be validated. Validation of

simulated yield data is important to ensure that they are compatible with historical yield obtained by an average grain farmer in Henderson County.

Given the unavailability of field specific historical yield data, EPIC simulated data were validated by comparing the average yield from five different soil types to county average yields over a ten year period. The choice of a shorter period of ten years, compared to the one actually used in the study (30 years of data) was motivated by the difficulty of de-trending the technology factor embodied in historical yields. Henderson county average yields were obtained from the National Agricultural Statistics Service (NASS) database.

A single rate fertilizer application across all soil types (or whole field production practice) was used for the validation. The fertilizer application level was chosen according to optimum cropping practices in Kentucky (Herbek et al., and Bitzer et al.). Fertilizer application rate used for validation (base line) were as follow: 198 kg.ha⁻¹ of N and 30 kg.ha⁻¹ of P for cor,, 36 kg.ha⁻¹ of P for soybeans; and 108 kg.ha⁻¹ of N for wheat. Corn was planted on April 15, soybeans on May 11, and wheat on October 15. For the simulated irrigated crop, fertilizer application was increased by 10 percent to account for additional fertilizer leaching.

The simulated data was validated using the student-t and F- statistical tests. These two tests were used to check whether simulated and county average yields for each crop had statistically identical mean and variance. A two-tailed test was performed at 99 percent confidence level. Results (Table 1) show that we failed to reject the null hypothesis that the two means and variances are significantly different for all crops but soybeans. This meant that both samples could have been drawn from the same population, and that their

means and variances were not statistically different. Only the soybeans variances were statistically different at the 99 percent, confidence level. This resulted from the high variance in the simulated yields data. Henderson County could have faced severe drought that affected soybeans yield. Coefficient of variation for the simulated soybeans yield was twice as high as the one of the county average. This might have resulted from the fact that the few selected soils in the simulation were not representative of the whole County. The double cropped soybeans and irrigated yield were not validated because of the unavailability of historical data. Once the model had been validated, 30 years of simulated data were generated for different planting dates, soil and fertilizer application levels.

Precision agriculture was modeled using soil specific VRA of fertilizer. This method of applying variable rate nutrient based on soil type was found to be more profitable than variable rate nutrient application based on grid sampling (Lowenberg-DeBoer and Aghib, Lowenberg-DeBoer, 1999). Here, five different soil types were chosen and believed to be representative of the soil types a representative farmer was likely to farm within a given geographic area. Five fertilizer levels were applied on each soil to generate five series of yield data for each crop. From the base line, fertilizer application levels were increased for the higher application rates by 15 and 30 percent, and decreased in the same proportions for the lower rates of application.

Planting date was also modeled as it represents an important risk management variable for the producer (Dillon). Four planting dates were chosen for corn and soybeans, and three planting dates for wheat. Planting dates were March 25, April 15, May 11 and Jun 05 for corn; April 15, May 11, Jun 05, and June 30 for full season and

double crop soybeans; and October 1, 15, and 30 for wheat. Other data used in the simulation and mathematical programming models will be discussed in the following section.

Other data

Within field-spatial-variability is an important component of the profitability of PA technology (English et al). The choice of five soil types in the model was made to guarantee minimum soil variability. The number and types of soil chosen were based on personal communication with Dr. Tom Mueller, and also on the Henderson County soil survey. According to Mueller, a typical farm in Kentucky usually contains four to five main soil types (Appendix 3). Soil types are usually found by association. Two of the most important associations in Henderson County are the Loring-Grenada and Memphis-Wakeland associations. The two associations make up more than 35 percent of the county's land, but a much larger percentage of the agricultural land as they are good agriculture lands. Loring, Granada, Memphis, and Wakeland were then chosen to simulate the crop yield data. A fifth soil, Huntington, also found in the region was added under the assumption that producers do not always have their crop land in the same geographical area. In that hypothetical farm, Memphis covered 240 acres of land, Loring 380 acres, Grenada 330 acres, Huntington 220 acres, and Wakeland 180 acres.

To obtain the irrigated yields data, the center-pivot irrigation method was chosen in EPIC. The center-pivot irrigation method was used in EPIC because the model did not have SDI as an irrigation option. Yield comparison trials done at Texas A&M University (Bordovsky et al.), however, show that SDI and center-pivot system produced almost identical results. Irrigation was automatically triggered when water stress reached 80

percent. Total annual irrigation was also limited to 10 acre-inches, an estimated irrigation water need for Kentucky conditions (Workman). The model assumes that all the water demanded by the crops was available at the time it was needed without considering the possibility of shortages. This assumption was realistic for Henderson County production conditions. The county borders the Ohio river and farmers usually have quasi unlimited access to irrigation water.

Other data used in the mathematical programming model included commodity price, PA and irrigation variable cost, or operating cost for conventional (or uniform rate) production practices. Commodity prices received by Kentucky producers were obtained from the National Agricultural Statistic Services (NASS) database. A five year (1999-2004) average price was used in the model. Operating costs for corn (Moss and Riggins), full season soybeans (Ramming et. al), double soybeans (Ramming et. al) and wheat (Heisterberg and Trimble) were obtained from Kentucky enterprise budgets. Additional fixed and variable costs generated by the usage of PA technology were obtained from a PA budget developed by Gandonou et al. Finally, variable irrigation costs were obtained from the University of Arkansas estimated production costs using the SDI system.

Results and analysis

An expected value variance (EV) model was used to compare the production practices and risk management strategies of a hypothetical Henderson County grain producer having to choose between three different production technologies: precision agriculture (PA), whole field management (WFM), or subsurface drip irrigation (SDI). To that end, five different scenarios were modeled and compared. In the first scenario, conventional production practice or (WFM) was modeled. In that scenario, the producer

chose the optimum crop mix, planting date, and fertilizer level that maximized profit. In the second scenario (PA), PA technology (variable rate fertilizer application) was used on dry land. In the third scenario (SDI-full), the farmer adopted irrigation as a unique production practice. Sub-surface drip irrigation equipment was installed on the entire production area and crops produced under conventional production practice (uniform rate fertilizer application). The constraint to irrigate the entire field was released in the fourth scenario (SDI-opt), and the producer could choose to only irrigate some crops in order to maximize profit. Finally, in the fifth scenario (PA/SDI), the producer could opt to use either PA, SDI, or both simultaneously. These five different scenarios would help determine the value added of either PA and/or SDI. Two additional scenarios, (six and seven) were modeled to evaluate the profitability of the PA custom hiring operation. Scenario six (CH-PA) was the equivalent of PA scenario and scenario seven (CH-PA/SDI) the equivalent of scenario five (PA/SDI) when the PA operation was custom hired

For the purpose of simplification, four levels of risk aversion were selected in addition to the risk neutral case. The selected Z score of the risk aversion parameter α were 50 percent for the risk neutral producer, 60 percent for the low risk averter, 70 percent for the medium risk averter, 80 percent for the high-risk averter, and 90 percent extreme risk averter. Planting dates were classified as early, good, late and very late.

In the following sections, production and statistical results of the risk neutral producer (the linear programming solution of the model) will first be presented for each scenario. Then, results for risk averse producers will be discussed.

Analysis of the risk neutral solution.

The risk neutral primary objective was to maximize the farm's net return above variable costs. An analysis of the economic results (table 2) shows that of the three available production strategies (WFM, PA, and SDI), WFM was the most profitable. The adoption and investment in PA resulted in a 3 percent decrease in expected net return above variable costs. The expected net return for the PA adopter choosing to purchase the equipment (scenario two, SDI-dry) was \$144,187 compared to \$148,441 in the conventional production scenario (WFM). Custom hiring PA (CH-PA) service proved to be slightly more profitable (\$146,428) than purchasing the equipment, but still less advantageous than WFM. Maximum attainable net return for PA (\$268,898) was, however, higher than that of conventional practice (\$244,829). This result confirms the Grusy survey results that 74.4 percent of the surveyed farmers using PA have used custom hiring services for variable-rate fertilizer application. The same survey also reported that grain farmers believe that the cost of PA was the greatest limitation to adoption.

Similar to PA, an investment in SDI (scenario three, SDI-full) was also found to be less profitable than conventional practices (WFM). The average increase of 16 and 23 bushels per acre respectively for soybeans and corn attributed to irrigation did not cover the cost of irrigation. An investment in the irrigation technology would have resulted in a loss of \$4571 compared to the conventional production strategy. Net return in the third scenario (SDI-full) was only \$143,870. Maximum attainable profit level on irrigated land (SDI-full) was \$180,298, compared to \$244,829 for conventional practice (WFM). The reduction in expected return could be explained by the fact that the entire cropping area

and all crops were irrigated. An alternative scenario (scenario four, SDI-opt) allowing the producer to choose between irrigation and dry land production practice showed that irrigation was more profitable than both PA and WFM. So, an investment in SDI was only profitable on selected areas of the field. Net return above variable costs was \$161,416 with a maximum profit of \$225,734.

In the fourth scenario (SDI-opt), a higher profitability level was achieved by producing corn exclusively on dry land. There was no irrigation investment cost incurred, and only a medium fertilizer rate was used. In the first four scenarios (excluding PA/SDI), the risk neutral farmer used approximately the same production strategy. Corn and full season soybeans were planted early respectively on March 25 and April 15. In the WFM and PA scenarios, soybeans were fertilized at a low rate. When irrigation was used, optimum yield was attained for soybeans by increasing the fertilizer level to high. In scenario one (WFM) and four (SDI-opt), the medium fertilizer application was the optimum application level. Finally, in the fifth scenario (PA/SDI), a combination of scenario two (PA) and four (SDI-opt) were utilized to optimize profitability. Soybeans were irrigated, but at a single high fertilization rate, and corn was produced on dry land using PA technology. Double crop soybeans and wheat never enter the optimum solution in any of the five scenarios for this risk neutral producer.

In scenarios four (SDI-opt) and five (PA/SDI), it could be observed that a selective utilization of irrigation could be the source of substantial profitability improvement. In those cases, SDI was used on selected crops only when it was the most profitable. The decision to selectively use irrigation in a specific area of the field to install SDI would, however, require field historical and spatial data. Only a careful analysis of yield and

other soil test data using PA technology could make these choices possible. This model should not, however, be assimilated into precision irrigation as not only the decision to irrigate need not to be exclusively spatially related but also the model does not allow for variable rates application of irrigation water.

In the fifth scenario (PA/SDI), the model was further relaxed to allow the producer to select whichever production method would maximize profitability. S/he could choose any combination of PA or SDI production method under irrigated or dry land condition, the objective being to assess the combined value of PA and WFM. Given these options, the producer was able to increase the operation's profitability to \$159,415 (with a maximum of \$252,058). This net return was still lower than the one obtained in the fourth scenario (SDI-opt). The investment cost in PA equipment appeared to affect profitability. When the producer custom hires the PA operation (scenario seven, CH-PA/SDI), s/he was able to reach the highest expected net return of all seven scenarios. By simultaneously using custom hiring services for the PA operation and investing in SDI (CH-PA/SDI), the farmer was able to attain a net return of \$181,520, which represents an increase of 18.2 percent, 20.6 percent, and 20.7 percent respectively compared to WFM, PA, and SDI-opt. Such result was achieved by adopting a production strategy different from the one used in scenario five (PA/SDI).

For the risk neutral producer, maximum profit was achieved by introducing double crop soybeans and wheat into the optimal solution. Double crop soybeans and corn were produced utilizing the PA custom service. In addition, soybeans were irrigated to obtain maximum yield. Corn however was not irrigated.

Analysis of the risk averse scenarios.

The underlying expected utility theorem takes into account the decision maker's perception of risk and the degree of risk aversion (Anderson et al.). To compare the producer's risk management behavior across all seven strategies, risk aversion parameters obtained from the first scenario (WFM) were used for the other six scenarios. The objective of the risk averse producer is to reduce the average income variability while maximizing the operation's net return above variable costs. In the following section, the production decisions made by the four risk averse farmers will be analyzed.

Compared to irrigation VRA technology did not appear to be an efficient production risk management tool. For the risk averse producer, the lowest income variability was achieved with the investment in the SDI technology (scenario three, SDI-full). The investment in the PA equipment not only increased the production risk the producer is exposed to but also lowered the expected net return. For all risk aversion levels, an investment in PA equipment resulted in a lower expected income and a higher variability compared to both WFM and SDI-full/opt. For a low risk averse producer, for example, such an investment reduced his/her expected income by \$2,512 while increasing the expected income variability from 22.9 percent to 23.7 percent compared to WFM. The loss of expected net return related to PA adoption increased as the risk aversion level increased. The extreme risk averse producer would have lost \$5,558 by adopting PA than by producing under WFM. Though PA adoption increased yield by 4 bu/ac for corn and soybeans and 2 bu/ac for wheat, the added revenue was not sufficient to cover the total additional fixed and variable cost. The situation was however somewhat different when the producer custom hired the PA operation.

The custom hiring alternative produced mixed results across risk aversion levels. The low and medium risk averse producers were able to increase their expected net return compared to the WFM option. For the low risk averse producer, custom hiring the PA service (CH-PA) would have generated an expected net return of \$142,428 (with c.v. of 23 percent); a \$1,642 increase in net return compared to the WFM scenario, but also a 1 percent increase in the c.v.

At the higher end of the risk aversion spectrum, the situation reverses as the WFM practice generated higher expected net returns, also associated with higher c.v. compared to the PA custom hiring case (CH-PA). As a result, there was always a trade off between the net return and risk level for adopters of the custom hired PA operation (CH-PA) and the WFM option. A higher expected net result in either case was associated with a higher c.v.

Based on the results from the two PA alternatives (PA and PA/SDI), it would be expected that the risk averse producer currently using WFM would not switch to PA as it increases his/her exposure to risk. Compared to PA, SDI-full proved to be the ideal production-risk management technology. For the low risk averter, the c.v. obtained with the irrigation option, SDI-full (10.8 percent), was less than half the one obtained with WFM (22.9 percent) or PA (23.7 percent). In addition to obtaining lower income variability, the producer investing in SDI (SDI-full) increased the farm's net income by \$680 compared to WFM. As risk aversion increases, the investment in the irrigation equipment becomes comparatively more attractive for the risk averse farmer. The extreme risk averse farmer using SDI-full could reduce his/her income variability to a c.v. of 7 percent while obtaining a net return \$11,797 higher than in the WFM case.

The financial benefits of SDI-full adoption were found to be even higher when the producer was given the option to irrigate the crops most responsive to irrigation (scenario four, SDI-full). Compared to the third scenario (PA), the option to selectively choose the irrigated crop would increase the net return by \$8,759, and the c.v. by 2.8 percent. Of the first five scenarios, the fourth one (SDI-opt) would be preferred by the risk averse producer. It enables him/her to install the SDI equipment only on a limited amount of his/her land area, and thereby obtain a substantially higher income level compared to the WFM while reducing the production risk. However, higher expected returns could be attained with a combination of SDI and PA production practices.

A combination of PA and SDI production practices enabled the producer to increase profitability while reducing the operation's production risk. From the five scenarios, the highest return was obtained when the producer was able to irrigate when it was most profitable, and custom hire the PA service. In the seventh scenario (CH-PA/SDI), expected net return and c.v. were \$175,696 and 13.9 percent, \$169,859 and 10.1 percent, \$163,433 and 7.0 respectively for the low, medium, and extreme risk averse farmer. The value added of the PA custom operation for the extreme risk averse producer already using SDI-full was \$25,831 compared to WFM). Purchasing both the SDI and the PA equipment was found not to be a viable alternative. In that scenario, the expected return was lower and c.v. higher than in the case where only the SDI technology was adopted.

On the production side, the risk averse farmer manages the production (or yield) risk by utilizing the optimum combination of crop, planting date or fertilizer application level that will minimize the yield variability. Production management results (table 4) show similarities in the risk management strategy for producers opting for the WFM or PA

option. In the WFM scenario, farmers with higher risk aversion level progressively lowered yield variability by reducing the number of planting dates, as well as the number of crops under production. The low risk averse producer planted 70 acres of double crop soybeans on April 15 and 179 acres on May 11. Wheat planting was spread over all three available planting dates, and all the corn was planted on March 25. The extreme risk averse producer however, only produced wheat and corn. Wheat was planted only at the good date on October 15 at a medium fertilization rate (a unique fertilizer rate was applied across all soils), and corn was planted on March 25. The producer adopting the PA production practice utilized a comparable production-risk management strategy. Here, the producer could apply different fertilizer rate on different soil types. As in the WFM case, the optimum production strategy for the extreme risk averse producer was limited to wheat planted on October 15, and corn planted on March 25. The increased in yield variability (higher c.v. in the case of PA adoption) could be explained by the broader soil management options available with PA adoption in order to maximize net return. The ability to variably apply fertilizer levels across soil types was also used as a management instrument. The high-risk averse producer used three different levels of fertilizer for wheat early planting instead of two for the low and medium risk averse producer. Yield variability was reduced by progressively reducing the total land area and crops produced.

Contrary to the previous scenarios, the producer using SDI (SDI-full) reduced yield variability by expanding the corn planting period window and increasing acreage. The low risk averse farmer chose to produce full and double crop soybeans, wheat and corn. The entire land area allocated to corn was planted early. Medium, high, and extreme risk

averters however diversified their production strategy by planting some acreage of corn on March 11. These three types of risk averse producers also adopted the same production plan for double crop soybeans and wheat. When given the option to produce under irrigated or dry land (SDI-opt), risk averse producers increasingly allotted more land area to irrigation. While the low risk averse farmer planted 529 acres of corn on dry land and 146 acres on irrigated land, the optimum plan for the high risk averse was 197 acres on dry land, and 309 on irrigated land. As risk aversion increases, the proportion of land produced under SDI increases and risk is additionally managed by extending the planting period. Double crop soybeans and wheat acreage also increase with risk aversion, whereas less and less full season soybeans are produced. This mixed production strategy enabled the risk averse producer to increase the expected net return compared to the situation where all the available cropping area was irrigated.

Summary and Conclusion

Precision agriculture (or variable rate fertilizer application) and the SDI system are two growing production technologies with potential production risk capabilities. This study examined the production risk management potential of the two technologies adopted individually or simultaneously. Precision agriculture being a multi-faceted technology, only the variable rate fertilizer application of the technology was considered. A biophysical simulation and mathematical programming were used to model the production environment of a Henderson County commercial grain farmer. The biophysical model simulated soybeans, corn and wheat expected yield on five different soil types and five levels of fertilizer application. In the mathematical programming

model an expected value-variance framework was used to determine the farmers production decisions depending on their level of risk preference.

Results indicate that compared to the conventional production practice, PA was not a better risk management technology. With the SDI installation however, the hypothetical farmer was able to substantially reduce yield variability while improving the operation's profitability. By combining SDI and PA both the risk neutral and risk averse farmers were able to substantially increase the farm operation's expected net return above variable cost, and reduce production risk. Though the combination did not permit them to attain a lower c.v. than SDI alone, the increase in net return was high enough to be considered by a risk averse farmer.

Table 2.1. Statistical Summary for Base line Simulated and County Yield Data.

Statistical Summary of Validated Yields												
	Corn				Soybean				Wheat			
	Simulated	County Avg.	Simulated	County Avg.	Simulated	County Avg.	Simulated	County Avg.	Simulated	County Avg.	Simulated	County Avg.
Mean	117.25	114.20	40.00	35.50	52.87	50.56						
StDev	17.91	16.36	6.47	3.01	10.57	10.87						
CV	15.27	14.33	16.17	8.47	20.00	21.51						
Min	85.80	89.00	29.31	31.00	35.31	29.00						
Median	120.91	111.50	40.81	35.00	52.18	52.00						
Max	148.21	146.00	52.17	40.00	66.85	67.00						
99% Confidence Level	Test Value	Critic al Value	P- Value	Decis ion	Test Value	Critic al Value	P- Value	Decis ion	Test Value	Critic al Value	P- Value	Decis ion
2 Sample t-Test	0.38	3.22	0.71	F-M	1.89	2.56	0.08	F-M	0.43	3.29	0.67	F-M
F-Test	1.20	5.35	0.40	F-V	4.62	3.18	0.02	R-V	1.06	6.03	0.47	F-V

F-M = Fail to Reject the Ho that the Means are Equal

F-V = Fail to Reject the Ho that the Variances are Equal

R-V = Reject the Ho that the Variances are Equal

Table 2. 2. Summary Statistics of the PA Equipment Investment Scenarios

Scenario 1: Uniform rate application of fertilizer on dry land					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	148441	140865	137472	134683	125805
Max (\$)	244829	194723	195704	194898	186419
Min (\$)	44865	77822	80210	81273	79814
Std. Dev (\$)	52750	32213	29235	27838	24153
C.V. (%)	35.5	22.9	21.3	20.7	19.2
Scenario 2: Variable rate application of fertilizer on dry land					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	144187	138353	136083	127768	120246
Max (\$)	268898	200427	190280	171967	163995
Min (\$)	29367	64578	65575	61872	61187
Std. Dev (\$)	58571	32819	31326	26966	23930
C.V. (%)	40.6	23.7	23.0	21.1	19.9
Scenario 3: Irrigation with single rate fertilizer application					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	143870	141545	139886	139126	137602
Max (\$)	180298	171878	166308	163915	158685
Min (\$)	91429	107716	115385	117459	119770
Std. Dev (\$)	21573	15238	12174	11144	9654
C.V. (%)	15.0	10.8	8.7	8.0	7.0
Scenario 4: Single rate fertilizer application under Irrigated or dry land					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	161416	156390	148645	144956	141799
Max (\$)	225734	210532	185179	172700	165022
Min (\$)	104831	112876	121986	122761	121913
Std. Dev (\$)	32972	26454	17178	13358	10730
C.V. (%)	20.4	16.9	11.6	9.2	7.6
Scenario 5: Irrigation and/or Precision Agriculture					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	159415	153609	145080	140745	136571
Max (\$)	252058	210875	186115	174087	161941
Min (\$)	94401	93460	102739	108237	115042
Std. Dev (\$)	38007	28377	18917	14903	11769
C.V. (%)	23.8	18.5	13.0	10.6	8.6
Neutral = 50% of risk significance level			High = 80% of risk significance level		
Low = 60% of risk significance level			Extreme= 90% of risk significance level		
Medium = 70% of risk significance level					

Table 2.3. Summary Statistics of the PA Custom Hiring Service Scenarios

Scenario 6: Custom Hire VRA of fertilizer on dry land					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	146428	142508	140186	131279	125363
Max (\$)	271139	204582	194329	173914	169117
Min (\$)	31608	68733	69691	65739	66311
Std. Dev (\$)	58571	32819	31294	26408	23928
C.V. (%)	40.0	23.0	22.3	20.1	19.1

Scenario 7: Custom Hire Precision Agriculture and/or Irrigation					
Risk Aversion	Neutral	Low	Medium	High	Extreme
Mean (\$)	181520	175696	169859	166777	163433
Max (\$)	267647	230059	209161	199986	189097
Min (\$)	114326	120281	131453	137209	142648
Std. Dev (\$)	35448	24474	17109	14027	11437
C.V. (%)	19.5	13.9	10.1	8.4	7.0

Neutral = 50% of risk significance level

High = 80% of risk significance level

Low = 60% of risk significance level

Extreme = 90% of risk significance level

Medium = 70% of risk significance level

Table 2.4. Production Management of the Different Scenarios by Risk Aversion Level

Scenario 1: Uniform rate application of fertilizer on dry land							
Crops	Planting date	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
Soybeans	AP15	low	675				
DC-Soybeans	AP15	low		70			
DC-Soybeans	MY11	low		179	225	191	
Wheat	OC01	high		248	225	191	
Wheat	OC15	med		248	225	292	675
Wheat	OC30	vhhigh		179	225	191	
Corn	MR25	low		162	384	483	507
Corn	MR25	med	675	513	291	192	168
Scenario 2: VRA of fertilizer on dry land							
Crops	Planting date	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
Soybeans	AP15	low	675				
DC-Soybeans	MY11	vlow		95	95	50	
DC-Soybeans	MY11	low		67	67	35	
DC-Soybeans	MY11	high		63	63	33	
Wheat	OC01	med				46	
Wheat	OC01	high		195	195	56	
Wheat	OC01	vhhigh		30	30	16	
Wheat	OC15	vlow		63	63	123	145
Wheat	OC15	med		132	132	256	440
Wheat	OC15	vhhigh		30	30	58	90
Wheat	OC30	vhhigh		225	225	118	
Corn	MR25	vlow	190	190	153	90	64
Corn	MR25	low	110	275	344	375	401
Corn	MR25	med	165	210	178	210	210
Corn	MR25	high	210				

Table 2.4. (continues). Production Management of the Different Scenarios by Risk Aversion Level

Scenario 3: Irrigation with single rate fertilizer application								
Crops	Planting date	Fertilizer Rate	Risk Aversion Level					
			Neutral	Low	Medium	High	Extreme	
Soybeans	AP15	high	675	162				
DC-Soybeans	AP15	med		256	338	338	338	
Wheat	OC01	high		256	338	338	338	
Wheat	OC15	med		256	338	338	338	
Corn	MR25	high	675	675	599	536	454	
Corn	MY11	high			76	139	148	
Corn	MY11	vhigh					71	
Corn	JN05	med					3	

Scenario 4: Single rate fertilizer application under Irrigated or dry land								
Crops	Production Strategy	Planting date	Fertilizer Rate	Risk Aversion Level				
				Neutral	Low	Medium	High	Extreme
Soybeans	IRR	AP15	high	675	402	154	47	
DC-Soybeans	IRR	AP15	med		137	260	314	338
Wheat	DRY	OC01	high		137	260	314	338
Wheat	DRY	OC15	med		137	260	314	338
Corn	DRY	MR25	low			10	34	45
Corn	DRY	MR25	med	675	529	311	197	120
Corn	IRR	MR25	high		146	264	309	315
Corn	IRR	MY11	high			89	135	148
Corn	IRR	MY11	vhigh					46

URA = uniform rate application of fertilizer (or whole field production)

VRA = variable rate application of fertilizer (or precision agriculture production)

IRR = Production on irrigated land DRY = Production on dry land

WF = Whole Field management strategy PA = Precision Agriculture management

FS-Soybeans = Full Season Soybeans DC-Soybeans = Double Crop Soybeans

MR15 = March 15, AP15 = April 15, MY11 = May 11, JN05 = June 05

OC1 = October 1st, OC15 = October 15, OC30 = October 30

Table 2.4. (continues). Production Management of the Different Scenarios by Risk Aversion Level

Scenario5: Irrigation and/or Precision Agriculture									
Crops	Production Strategy 1	Production Strategy 2	Planting date	Fertilizer Rate	Risk Aversion Level				
					Neutral	Low	Medium	High	Extreme
Soybeans	WF	IRR	AP15	high	675	284	92	21	
DC-Soybeans	WF	IRR	AP15	med		195	291	327	338
Wheat	WF	DRY	OC01	high		195	291	327	338
Wheat	WF	DRY	OC15	med				16	155
Wheat	PA	DRY	OC15	vlow		55	82	88	51
Wheat	PA	DRY	OC15	med		114	170	190	107
Wheat	PA	DRY	OC15	vhigh		26	39	34	24
Corn	WF	IRR	MR25	high		51	276	349	344
Corn	WF	IRR	MY11	high				40	102
Corn	WF	IRR	MY11	vhigh					34
Corn	PA	DRY	MR25	vlow	190	176	112	80	55
Corn	PA	DRY	MR25	low	110	254	163	116	79
Corn	PA	DRY	MR25	med	165	143	119	89	61
Corn	PA	DRY	MR25	high	210	51	5		

Table 2.4. (continued). Production Management of the Different Scenarios by Risk Aversion Level

Scenario 6: Custom Hire VRA of fertilizer on dry land							
Crops	Planting date	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
Soybeans DC-	AP15	low	675				
Soybeans DC-	MY11	vlow		95	94	33	
Soybeans DC-	MY11	low		67	66	23	
Soybeans	MY11	high		63	63	22	
Wheat	OC01	med				12	
Wheat	OC01	high		195	194	56	
Wheat	OC01	vhigh		30	30	10	
Wheat	OC15	vlow		63	64	146	145
Wheat	OC15	med		132	133	303	440
Wheat	OC15	vhigh		30	30	69	90
Wheat	OC30	vhigh		225	224	78	
Corn	MR25	vlow	190	190	153	103	63
Corn	MR25	low	110	275	343	362	402
Corn	MR25	med	165	210	179	210	210
Corn	MR25	high	210				

Table 2.4. (continued). Production Management of the Different Scenarios by Risk Aversion Level

Scenario 7: Custom Hire Precision Agriculture and/or Irrigation									
Crops	Production Strategy	Production Strategy	Planting date	Fertilizer Rate	Risk Aversion Level				
					Neutral	Low	Medium	High	Extreme
DC-Soybeans	PA	IRR	AP15	med	338	338	338	338	338
Wheat	WF	DRY	OC01	high	338	338	338	338	338
Wheat	WF	DRY	OC15	med	338				119
Wheat	PA	DRY	OC15	vlow		95	95	95	62
Wheat	PA	DRY	OC15	med		239	220	223	142
Wheat	PA	DRY	OC15	vhigh		3	22	20	15
Corn	WF	DRY	MR25	med		65	149	141	95
Corn	WF	IRR	MR25	high		146	320	370	358
Corn	WF	IRR	MY11	high				46	105
Corn	WF	IRR	MY11	vhigh					33
Corn	PA	DRY	MR25	vlow	190	131	58	33	24
Corn	PA	DRY	MR25	low	110	189	84	48	35
Corn	PA	DRY	MR25	med	165	62	64	37	27
Corn	PA	DRY	MR25	high	210	82			

Chapter 3. Precision Agriculture versus Whole Field Farming: A Financial Risk Analysis

Introduction

The farming operation is one that involves a significant level of risk and uncertainty. Finding means and ways to reduce the level of risk farmers are exposed to had long captured the interest of many researcher in various disciplines in agricultural. In 1997 an Iowa Farm and Rural Life Poll showed that a large majority of producers (66%) think that risk in farming has been increasing (Lesley). To respond to these increasing challenges, the results of the pool indicated that farmers primarily choose crop insurance, debt reduction, diversification and forward contracts as risk management tools.

Another mean to respond to the new challenges faced by producers is the continuous adoption of new and more efficient technologies. Today, precision agriculture (PA) is a technology that can enable farmers to increasingly integrate and take control of the production process. A comprehensive literature review on the profitability of PA by Lambert and Lowenberg-DeBoer shows that 73% of the studies reported found that PA was more profitable than conventional production methods. In addition, PA also has the potential of being more environmentally friendly than conventional production methods.

In spite of its great potential, there are still a significant number of obstacles obstructing the full development of the PA technology and its adoption by a majority of US farmers. Many reasons have been advanced to explain the low rate of PA adoption by US farmers. Among them are, the high cost of adoption (Cook et al.), low profitability (Lowenberg-DeBoer (1997a), Bullock et al.), lack of perceived opportunities delivered

by PA (Douglas, et al), or the unwillingness to replace existing equipment (Khanna, Epouhe and Hornbaker).

In effect, cost of adoption and unwillingness to accept greater financial risk rank high among the reasons for non-adoption. Daberkow and McBride found that adopters of PA technology have a considerably higher debt-to-asset ratio, which indicates a willingness to accept greater financial risk. Yet, the debt-to-asset ratio alone does not reflect the overall financial risk the farmer is taking while making an investment. Liquidity risk also represents a key component of the financial risk as it measures the producer's ability to meet his/her financial obligations after the investment is made. Ultimately, one of the main concerns often expressed by producers is the financial viability of the farm over time. Therefore, consideration of time in the decision-making process becomes a key element. To alleviate one of the biggest concerns about the financial risk related to the investment in new technologies it becomes necessary to demonstrate that such an investment will not threaten the farm's financial stability and survival.

The objective of this article is to analyze the financial risk associated with an investment in PA technology and irrigation. Pursuing a profit maximization objective may not always be financially feasible for the decision maker. Because of the new developments in the subsurface drip irrigation (SDI) system and its potential interest for Kentucky producers, it was found useful to include both PA and SDI technologies in the analysis. The financial impact of an investment in PA technology and/or irrigation system on risk taking behavior, profitability and production decisions made by a typical Kentucky grain producer will be evaluated using a discrete stochastic sequential programming (DSSP) model.

Methodologically, this article contributes to the literature of agricultural economics as it is the first paper that uses a discrete stochastic sequential programming (DSSP) model to analyze the impact of technology adoption on the farm's financial risk. The model developed here displays a unique and innovative application of DSSP in financial risk analysis.

The article is organized as follow. First, a background on risk management in general and financial risk in particular will be presented. Second, the modeling approach used will be discussed followed by the empirical description of the farm model. Third, the farming situation and the model's data are presented, and finally, results are reported followed by the conclusion.

Agriculture financial risk

The ability to manage various types of risk is critical for a good farm manager. There are five main sources of risk most farmers are exposed to: production or yield risk, price or market risk, human or personal risk, institutional risk, and financial risk (Harwood et al.). Farmers' sensitivity to different sources of risk depends, among other things, on the type of crop or livestock they produce. According to the 1996 USDA Agricultural Resource Management Study (ARMS) survey wheat, corn, soybean, cotton and tobacco producers were primarily concerned about yield and price risk. Next are institutional risk and human and personal risk. This classification however varies from year to year. The financial risk differs from other risk because it results from the way the firm's capital was obtained and financed on the short and the long term. Having an exact knowledge of the financial situation of the farm is a key element for decision-making in

the production process as well as in other areas. Therefore, managing the financial risk is a key element of a farm's overall risk management.

Five broad categories of performance measurement can be used by farmers to better understand their farm business: liquidity, solvency, profitability, repayment capacity and financial efficiency (Crane). The analysis of each category is necessary to fully assess the financial situation of the business. In this paper, only solvency was considered. In effect, a farm business that is not solvent will find it almost impossible to obtain any credit from lenders. The solvency measure provides an indication of the business' ability to repay all its debts. It also gives an indication of the farmer's ability to continue its operation after a financial shock. There are three financial ratios commonly used to measure solvency: the debt-to-asset ratio, the equity-to-asset ratio and the debt-to-equity ratio. The three ratios provide a very similar type of information. The debt-to-asset ratio, which was used here, expresses the farm's total liabilities as a proportion of its assets. It can also be described as an indication of the relative dependence of farm businesses on debt and their ability to use additional credit without impairing their risk-bearing ability. This ratio is one of the main components of the farm financial analysis and what lenders consider in their decision to provide a loan.

The intensification in capital requirement in today's production environment pushes farmers to carry heavier and heavier debt loads. When commodity prices are at their lowest as they have been in recent years, debt repayment capability can become a serious issue for some farmers. About the 1997-1999 price crisis, Wirtz writes: "most sources generally agreed that indebted farmers would have the toughest time dealing with low prices, as lower farm receipts will make it virtually impossible to cash-flow their

operation while paying off existing debt” (page 3). The pressure of a high level of debt and a higher debt-to-asset ratio might force some farmers to reconsider investing in new technology equipment with uncertain returns. A consistent risk management strategy and the subsequent production decisions is one of the main elements that will insure the survival of the business. The debt to recovery ratio was a second financial ratio utilized to evaluate the farm’s financial situation after an investment in PA equipment was made.

Modeling Framework

Investment in a new technology may not be a straightforward decision for a farm manager to make. Not only is such an investment associated with the uncertainty related to the additional stream of income the new investment will engender as opposed to its total annual cost, but marketing and other risks also need to be considered. Prior to the investment decision, the farmer will have to consider stochastic variables such as future commodity price, crop yield, interest rates, production costs, or agricultural policy. In addition the stochastic aspect of the farmer’s investment decision, there is also a dynamic aspect due to the linkages between current and future decisions.

Because farmers typically make investment decisions in consideration of the long term impact of that decision on most aspects of their business, modeling of investment decisions usually requires use of a sequential or multi-period programming model. In such models, financial elements such as liquidity or debt to asset ratios can be included, but when risk is modeled, the risk factor will ultimately be essentially captured in the objective function. Modeling both the stochastic and dynamic components of the farm’s financial decisions was done here using a discrete stochastic sequential programming (DSSP) approach. DSSP is a mathematical programming method that can be used to

model uncertainty in both the right-hand sides and technical coefficients. Conceptually it incorporates all sources of uncertainty: right hand side, objective function and technical coefficients while allowing adaptive decisions. In this type of model, decisions in a later stage are “influenced not only by the occurrence of particular random events in that stage, but also by random outcomes and decisions made in earlier stages” (page 16) (Apland and Kaiser).

The model is an investment decision model. In this type of model, the random effect of price and interest rate variability play an important part in the ultimate investment decision. Analysis of the financial sustainability of the business following the investment was limited to three stages or periods (t_1 , t_2 , and t_3) when the annual financial load due to the investment is the most important. It is assumed in the model, that the farmer has full knowledge about the outcomes of the previous stages $t-1$. The DSSP problem can be formulated as a quadratic programming problem, since all variability in the programming coefficients is eventually reflected in the objective function. In this way, an efficient E-V boundary can be generated and the strategy that maximizes expected utility can be located.

The Model

The mathematical programming model reproduced the production environment of a hypothetical Henderson County, Kentucky, grain farmer producing corn and soybean. S/he can choose to use precision agriculture technology (variable rate application of fertilizer), irrigation, or both. The current study relies upon the expected value variance (E-V) utility framework. This analytical framework is also often described as a DSSP/EV model (Apland and Kaiser). The objective function maximizes the ending farm net worth.

For the purpose of conciseness, only the second period of the model will be formulated here. For the full formulation of the model, refer to appendix 4.

To present the mathematical model, notation is defined in this section. Variables will be in upper case and parameters will be in lower case.

Objective function:

$$\text{Max } \overline{NW3} - \Phi \sigma_{NW}^2$$

Subject to constraints (1) to (19):

There are two types of constraints: production constraints (1) to (9), and accounting constraints (10) to (19).

$$(1) \quad \sum_E \sum_P \sum_F \sum_D \text{ACRE}_{E,P,F,D,S,t,j} \leq \text{acrelim}_{S,t,j} \quad \forall S, t=2, \text{ and } j=1, \dots, 9$$

$$(2) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{input}_{IPF} * \text{ACRE}_{E,P,F,D,S,t,j} - \sum_I \text{IPURCH}_{I,t,j} \leq 0 \quad \forall t=2 \text{ and } j=1, \dots, 9$$

$$(3) \quad \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"W"}, P, F, D, S, t, j} - \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"B"}, P, F, D, S, t, j} \leq 0 \quad \forall t=2, \text{ and } j=1, \dots, 9$$

$$(4) \quad \sum_P \sum_F \sum_D \sum_S \text{ACRES}_{\text{"C"}, P, F, D, S, t, j} - \text{ACRE}_{\text{"W"}, P, F, D, S, t, j} - \text{ACRE}_{\text{"B"}, E, P, F, D, S, t, j} \leq 0 \quad \forall t=2, \text{ and } j=1, \dots, 9$$

$$(5) \quad \text{acrelim}_{S'} * \text{ACRE}_{E, P, F, D, S, t, j} - \text{acrelim}_S * \text{ACRE}_{E, P, F, D, S, t, j} = 0 \quad \forall P = \text{WFM}, F, D, S \neq S', t=2, \text{ and } j=1, \dots, 9$$

$$(5') \quad \text{acrelim}_{S'} * \sum_E \text{ACRE}_{D, P, F, S} - \text{acrelim}_S * \sum_E \text{ACRE}_{D, F, S', P} = 0$$

$$\forall P = PA, F, D, S \neq S'$$

$$(6) \quad \sum_E \sum_P \sum_F \sum_D \sum_S 1/\text{yr YLD}_{E,D,S,P,F} * \text{ACRE}_{E,P,F,D,S,t,j} - \text{SALES}_{t,j} \leq 0$$

$$\forall t=2, \text{ and } j=1, \dots, 9$$

$$(7) \quad \sum_E P_{C,t,i} * \text{SALES}_{E,j} - \sum_I IP_I * IPURCH_{I,t,j} - NR_{t,i,j} = 0$$

$$\forall t=2, i=1, \dots, 81, \text{ and } j=1, \dots, 9$$

$$(8) \quad \sum_E \sum_S \sum_F \sum_D \text{ACRE}_{E,P,F,D,S,t,k} - IPA_{t,j} - IPA_{t,k} \leq 0$$

$$\forall P=PA, t=3, j=1, \dots, 9, \text{ and } k=1, \dots, 81$$

$$(9) \quad \sum_E \sum_S \sum_F \sum_D \text{ACRE}_{E,P,F,D,S,t,j} * IC - ISDI_{t,j} \leq 0$$

$$\forall P=SDI, t=2, \text{ and } j=1, \dots, 9$$

$$(10) \quad EASSET_{t,i,j} - EDEBT_{t,i,j} - NW_{t,i,j} = 0 \quad \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(11) \quad EASSET_{(t-1),j} + CBAL_{t,i,j} + LBOR_{t,i,j} - DEP_{t,i,j} - EASSET_{t,i,j} = 0$$

$$, \quad \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(12) \quad EDEBT_{t-1,j} + LBOR_{t,i,j} + KPAID_{t,i,j} + SBOR_{t,i,j} - EDEBT_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(13) \quad NR_{t,i,j} + CBAL_{t-1,j} - KPAID_{t,i,j} - IPAID_{t,i,j} - CBAL_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(14) \quad \sum_I IP_I IPURCH_{I,t,j} - CBAL_{t-1,j} + \text{min_cash} - SBOR_{t,i,j} \leq 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(15a) \quad ISDI_{t,j} + IPA_{t,j} - LBOR_{t,i,j} = 0 \quad \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(16) \quad lti * (LBOR_{t,i,j} + EDEBT_{t-1,j}) + sti_{t,i} * SBOR_{t,i,j} - IPAID_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(17) \quad (\text{bdebt}/20) + (\text{ISDI}_{t,j}/10) + (\text{IPA}_{t,j})/5 + \text{KPAID}_{(t-1)j} - \text{KPAID}_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(18a) \quad (\text{ISDI}_{t,j}/10) + (\text{IPA}_{t,j}/5) + \text{DEP}_{(t-1)i1} - \text{DEP}_{t,i2,j} = 0 \quad \forall t=2, j=1, \dots, 9, i1=1, \dots, 9, \text{ and } i2=1, \dots, 81$$

$$(19) \quad \overline{NW3} = \alpha_{Ti} (1/i * k) * NW3_{t,i,k} \quad \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81$$

variables:

$\overline{NW3}$ is the average expected net worth at the end of the period ($t=3$)

$\text{ACRE}_{E,D,S,P,F,t,j}$ is the number of acres produced for enterprise E on planting date D, soil S under production strategy P (“PA” for precision agriculture, “SDI” for subsurface drip irrigation, “WFM” for whole field management, and “D” for dry land) and fertilizer level F for period t and state of nature j

$\text{CBAL}_{t,i}$ is the cash balance for period t and state of nature i

$\text{DEP}_{t,i}$ is the total depreciation amount for periods t and state of nature i

$\text{EASSET}_{t,i}$ is the ending asset for period t for state of nature i

$\text{EDEBT}_{t,i}$ is the ending debt for period t for state of nature i

$\text{IPA}_{t,j}$ is the binary variable for the PA investment decision

$\text{IPAID}_{t,i}$ is the interest rate paid in period t and state of nature i

$\text{IPURCH}_{I,t,i}$ is the purchase of input type I in period t and state of nature i

$\text{ISDI}_{t,i}$ is the total irrigation investment made in a given period i

$\text{KPAID}_{t,i}$ is the debt’s principal payment for period t and state of nature i

$\text{LBOR}_{t,i}$ is the long term capital borrowed in period t and state of nature i

$NR_{t,i}$	is the net return above variable cost for period t and state of nature i
$NW_{t,i}$	is the expected net worth for period t and state of nature i
$SALES_{t,i}$	is the total farm sales for period t and state i (\$)
$SBOR_{t,i}$	is the short term capital borrowed for period t and state of nature i

indices:

E	represents the different enterprises (corn “C”, wheat “W”, and full season or double crop soybean “B”)
P	is the production strategy and includes irrigation (SDI), variable rate application (VRA or PA), and whole field management (WFM).
S	represents the five soil types (Grenada, Huntington, Loring, Memphis, and Wakeland)
F	is the fertilizer application levels (very low, low, medium, high, and very high)
D	represents the planting dates for each crop. “PS”, and “PW” respectively refer to double crop soybean and wheat planting dates.
I	is the quantity of input applied on each soil
t	denotes the period in which a decision was made ($t=1,\dots,T$), where T is the end of the planning horizon;
i	is the number of states of nature at time t
j	is the number of states of nature at time $t-1$
k	is number of states of nature at time $t-1$ and $t-2$

Y_r is the number of years

Coefficients and parameters:

Φ is the Pratt risk-aversion coefficient

IP_I is the input price by input type (I)

P_E is the price of crop E in dollar per bushel including related costs

$ACRELIM_S$ is the total number of acres available to the farmer by soil type S

$YLD_{E, D, S, P, F}$ is the expected yield during year t for enterprise E at planting date D, under production strategy P, on soil type F (in bushels per acre)

$input_{I P F}$ is the input I required by production strategy and fertilizer level

$sr_int_{t, i}$ is the short term interest rate for period t and state of nature i

Scalars include:

lr_int is the long term interest rate for investment capital borrowing

ic is the per acre SDI equipment fixed cost

$invk_pa$ is the total capital amount invested in precision agriculture

$basset$ is the beginning asset value and is set at \$1,525,000 p18 (Ibendahl)

$bdebt$ is the beginning debt value and is set at \$499,000 p18 (Ibendahl)

$bcbal$ is the beginning working capital value at \$129,254 p18 (Ibendahl)

Constraints description

- (1) land resource availability constraint
- (2) input purchase balance by input type
- (3) soybean and wheat planting schedule
- (4) crop rotation constraints

- (5) ratio constraint to control for non-variable rate management strategy under WFM or uniform rate fertilizer application
- (5') ratio constraint to control for non-variable rate management strategy under PA or variable rate fertilizer application
- (6) sales balance
- (7) profit balance
- (8) precision agriculture investment constraint
- (9) subsurface drip irrigation (SDI) investment constraint
- (10) expected ending net worth
- (11) ending asset
- (12) ending debt
- (13) cash balance constraint
- (14) short term borrowing
- (15) long term borrowing
- (16) interest paid on borrowing
- (17) reimbursement of the debt principal
- (18) total investment depreciation
- (19) objective function constraint

In this model, assuming that prices and interest rates are not correlated, a combination of four prices and three interest rates were used, resulting in 12 different states of nature in each period.

Data and Equations Description

The objective function maximizes the farmer's terminal net worth in period three after all production and investment decisions have been made. The producer had to make, both production and financial investment decisions in order to maximize his/her terminal net worth. The first constraint (1) limits the land area available per soil type. The decision to produce in period t is based on the states of nature from the previous period j . Out of the 1350 acres available to the hypothetical Henderson County grain producer (Morgan), Memphis covered 240 acres of land, Loring 380 acres, Grenada 330 acres, Huntington 220 acres, and Wakeland 180 acres (see Appendix 3). In the second constraint (2) it was assumed that the producer does not purchase more input than required. The third constraint models the feasible planting date sequences for double crop soybean preceding wheat. Equation (4) is the corn, soybean, and wheat rotation constraint. Equations (5) and (5') are ratio constraints to control for uniform (5a) and variable rate (5b) fertilizer application. The sales balance constraint (6) states that the farmer cannot sell more than s/he produces each year. Yield risk was not modeled here, and the average of 30 years of expected yield was utilized. Equation seven (7) represents the annual profit balance. The expected net return ($NR_{t,i,k}$) at the beginning of the current period is stochastic by nature as it is determined by the expected crop price in the current period, but also by the production of the previous period. Constraint (8) is the PA investment decision. By making the decision to invest in PA, the producer incurs the annual fixed cost of the PA equipment. $IPA_{t,j}$ is a binary variable for the investment in the PA equipment. Similarly, constraint (9) is the SDI investment decision constraint that computes the total irrigation equipment cost.

Constraint (10) determines the ending net worth for each period. In constraints (11a) and (12), the hypothetical farmer starts with a beginning debt of \$499,000 and a beginning asset of \$ 1,525,000 (Ibendahl et al.) representing the farmer's total debts and assets at the beginning of period one. In constraints (11) and (12), ending assets and debts are transferred from period to period. The cash balance constraints (13) is the total available cash. The available cash on hand is a function of the expected net return and associated investment cost. In situations of shortfall, the producer would have to borrow the amount of money necessary to continue the farming operation (14). In equation (15), it was assumed that the entire capital required for the investment in the new production equipment was borrowed. Total interest paid in constraints (16) is dependent on the probability that a given short term ($\beta_{t,i}$) interest rate occurs in a given period and state of nature. Historical interest rate data were obtained from Stam et al. In this model, the fixed principal amortization method was used to calculate the total amount of debt reimbursed each year, and equation (17) computes the annual fixed principal payment to be made. A 10 year debt repayment period was assumed for SDI, and five years for PA. In constraint (18), the useful life of the equipment was assumed to be fifteen years for the SDI and seven years for PA. The per acre SDI investment cost was obtained from Lamm, and total PA investment cost from Gandonou et al.

The yield data used in this model were obtained using the Erosion-Productivity Impact Calculator (EPIC). EPIC (Williams et al. 1984) was originally developed in 1981 to conduct a national survey of U.S. agricultural land. The model was then tested and validated in a number of studies (e.g. Williams and Renard; Bryant et al., Watkins et al.).

Details of the calibration and validation procedure used for this research are detailed in the previous chapter.

Other data used in the mathematical programming model include commodity price, PA and irrigation variable cost, or operating cost for conventional (or uniform rate) production practices. Commodity prices received by Kentucky producers were obtained from the National Agricultural Statistic Services (NASS) database. A five year (1999-2004) average price was used in the model. Operating costs for corn (Moss and Riggins), full season soybean (Ramming et. al), double soybean (Ramming et. al) and wheat (Heisterberg and Trimble) were obtained from Kentucky enterprise budgets. Additional fixed and variable costs generated by the usage of PA technology were obtained from a PA budget developed by Gandonou et al. Finally, SDI variable irrigation costs were obtained from the University of Arkansas.

Results

The objective in this paper was to evaluate the impact of an investment in PA equipment on the farm's ending net worth and financial status. To that end, the farm's financial indicators and production decisions were compared and analyzed in two different models and under two different scenarios. In the first model, the farmer produced under whole field management (WFM) practices, which represents the traditional production environment. In the second model, the farmer invested in PA and adopted the variable rate production management practice. Two different scenarios were considered for each model. The first scenario is the financial risk scenario modeled and described above where the farmer is exposed to price and interest rate risk. The second scenario described the situation where the producer is essentially exposed to yield risk,

price and interest rate remaining unchanged. The yield risk model used here was a combination of the production risk model in chapter two to which the previously described accounting equations added and a new objective function defined. The 30 year states of nature defined as “n” in chapter two were replaced by the states of nature in periods one, two, and three. Each state of nature in the new model represents a ten year yield average from the production risk model (chapter two). The advantage of comparing these two scenarios relies on the ability to examine the impact of financial (price and interest rate) and production (yield) risk on the farm operation’s financial situation, particularly in the case of an investment in PA equipment. The net worth at the end of each period was computed based on the expected gross returns and does not include the farmer’s living cost, tax, and other fixed costs.

The economic and production results were presented in tables one and two for the risk neutral farmer, and in tables three and four for the low risk averse producer. Results for higher risk averse farmers were not presented because there were no observed changes in production strategies across risk aversion levels. As risk aversion increases, the results show that producers would simply reduce the amount of acreage produced.

The net worth at the beginning of the period for all models and scenarios was \$1,026,000 and the working capital \$129,254. The model results show that the risk neutral producer tends to perform financially better in the financial risk scenario than in the production risk scenario. In the WFM model, the ending net worth in the scenario where the farmer faced price and interest rate risk alone increased by \$314,735 to \$1,340,735 at the end of the third period. Comparatively, the net worth in period three was \$1,459,597 in the yield risk scenario. The difference between the two scenarios is

explained by the higher net returns obtained in the yield risk scenario in both periods two and three. The expected net return above variable cost in the first scenario was \$148,441 for the first period, \$115,075 for the second, and \$69,784 in the third period. These expected net returns are respectively 26% and 30% higher in periods two and three in the second scenario than in the first one. The expected net returns in the yield risk scenario were \$148,441, \$155,786, and \$100,274 respectively in periods one, two, and three.

The profitability difference between the two scenarios can be explained, in part, from the model design. Financial risk was modeled by assigning an equal probability distribution to price and short term interest rate in each state of nature. Yield varied only by planting date and uniform fertilizer rate application level. Yields data were identical for all states of nature, therefore limiting the producer's ability to manage production risk. In the yield risk scenario, however, the producer was exposed to the same price in each state of nature, but different weather scenarios. An optimum production strategy can therefore be found for each state of nature in order to maximize the expected ending net worth in the case of the risk neutral producer, or reduce income risk in the case of the risk averse farmer. The resulting production strategies are presented in table 2 for the risk neutral farmer and in table 4 for the risk averse farmer. Though details on fertilizer application level were not presented in the result tables for the sake of conciseness in the results presentation, they will be briefly mentioned in the production strategy analysis.

To maximize the net return the risk neutral farmer in the production risk scenario adopted a diversification strategy by planting over a longer planting window. Corn was planted in March and in April in period two, while soybean sowing was spread out from April 15 to June 30 in period three. By managing the yield risk, the farmer also used the

optimum uniform fertilizer rate in each state of nature. Such management options were not available in the price and interest rate risk scenario resulting in more limited production management option. The optimum crop rotation, however, was identical in each scenario. Corn and soybeans were planted in the second period and double cropped soybeans and wheat entered the optimum solution in the third period.

Similar to the risk neutral farmer, the risk averse producer (tables 4) was able to reduce the ending net worth variability by further extending the available planting window for all crops. Double cropped soybean planting was spread from April 15 to June 30, and corn from March 25 to June 5. This diversification was made possible because in the yield risk scenario, the farmer is exposed to a different weather scenario at each state of nature, resulting in more diverse production management choices, on average.

The greater variability in weather conditions made it more difficult for the risk averse farmer to manage the ending net worth variability in the yield risk scenario. The coefficient of variability (c.v.) in the yield risk scenario was 0.267% compared to 0.09% in the financial risk scenario. The situation was similar for the PA investment model. The coefficient of variation in the yield risk scenario (0.27%) was also higher than the one in the financial risk scenario (0.11%). The risk averse producer in the financial risk scenario was able to obtain a lower net worth variability while achieving a higher net worth (\$1,299,383) compared to the yield risk scenario where the net worth was \$1,187,147. This result holds for both models and it suggests that the financial risk scenario would be a preferred scenario for the risk averse farmer whereas the risk neutral farmer obtained a higher ending net worth in the yield risk scenario.

Considering an investment in and adoption of the PA technology, it results in an increase in the expected net worth in the financial risk scenario, and a decline in the yield risk scenario compared to the WFM model for both risk neutral and risk averse producers. The ending net worth for the risk neutral producer investing in PA increased by 0.26% in the financial risk scenario while decreasing by 0.54% in the yield risk scenario. The impact of the PA investment on the farm's terminal net worth was not, however, an exclusive indicator of its financial health. The impact of the investment on the expected net return (ENR) was also an important element to consider when analyzing the financial impact of the investment.

An investment in PA equipment and adoption of the variable rate fertilizer production practice enabled the producer to increase the farm operation's net return in each scenario. For the risk neutral producer for example, the ENR in the financial risk scenario was \$111,368 with the PA investment model compared to \$69,784 without the investment. In spite of the improved profitability enabled by the investment, the weight of the PA investment generally had a relatively small impact on the farm's financial indicators.

Compared to the first model, an investment in PA equipment negatively impacted the debt to recovery ratio. This means that the level of resources available to pay existing debt was proportionally lower in the case of an investment in PA equipment than it was in the WFM model. So, though the switch in technology improved the farm's profitability, most of the added profit in some cases was used to serve the new financial constraints. For the risk neutral producer in the financial risk scenario, for example in period two (P2), 59.8% (one divided by the DTR of 1.67) of the income available for

debt coverage could be allocated to the payment of principal and interest. This debt repayment capacity (for the payment of existing long term debt) was 60.6% in the WFM model. In the yield risk scenario, however, the DTR was higher in the PA model than it was in the WFM model, mainly due to higher net returns. In that case, the increase in expected net worth more than compensated for the additional financial cost generated by the investment. This improvement could also be traced back to the working capital.

The working capital that measures how much liquid assets the operation has available to meet all its financial obligations was consistently lower in both scenarios when the PA investment was made in the risk neutral scenario. Though 29% lower than what it was in the WFM model, it could be expected that the risk neutral producer investing in PA would be in a position to cover the operation's fixed costs and tax liabilities with a working capital of 127,062.

The impact on the debt to asset ratios was also minimal with the investment in the PA. The debt to asset ratio increased by one percentage point from 33% to 34% for the risk neutral producer in the financial risk scenario. For the risk averse producer, the debt to asset ratio increased from 35% to 37%, the highest increase of all the scenarios. The relatively low impact of the investment in the financial ratios can be explained by the proportion of the investment compared to the farm's current existing long term debt and total net worth. The cost of the precision agricultural equipment represents 6.3% of the farm's total debt and 3% of its net worth.

Conclusion

For the risk neutral farmer, an investment in PA generally led to a deterioration of the farm's financial situation. The working capital needed to run the farm's daily

operations was lower, but did not appear to expose the operation to a financial crisis. The debt to asset ratio was higher by one percentage point in the third period and the debt to recovery ratio lower than in the WFM model.

In the risk averse case however, the investment appears to be generally positive in the financial risk scenario. In that scenario, the investment increased the expected net returns and the net worth and improved the available working capital as well as the farm operation's ability to pay the existing debt. The debt to asset ratio was, however, increased by one percentage point. The situation was, on the other hand, less enviable in the yield risk scenario where the investment in PA came at a higher cost: lower expected net worth, lower working capital, and much higher debt to asset ratio.

Table 3.1. Economic and Financial Data for the Risk Neutral Farmer

Risk Neutral Farmer	Whole Farm Management		Precision Agriculture	
	Price & Int. Rate Risk	Yield Risk	Price & Int. Rate Risk	Yield Risk
Net Worth P3 (\$)	1,340,735	1,459,597	1,344,267	1,451,769
Max Net Worth P3 (\$)	1,434,302	1,661,963	1,435,167	1,688,689
Min Net Worth P3 (\$)	1,285,216	1,202,626	1,294,904	1,166,666
Std. Dev. Net Worth P3 (\$)	97,489	105,614	46,329	113,332
C.V. Net Worth P3 (%)	7.270	7.236	3.450	7.810
Net Return P1 (\$)	148,441	148,441	148,441	148,441
Net Return P2 (\$)	115,075	155,786	118,740	159,327
Net Return P3 (\$)	69,784	100,274	111,368	137,078
Max Net Return P3 (\$)	106,702	143,204	146,575	204,959
Min Net Return P3 (\$)	50,139	50,448	0	65,975
Std. Dev. Net Return P3 (\$)	26,141	31,768	34,445	47,337
C.V. Net Return P3 (%)	37.46	31.68	30.96	34.53
Working Capital P3 (\$)	163,905	241,033	127,062	159,441
Debt to Recovery Ratio P1	2.71	2.71	2.71	2.71
Debt to Recovery Ratio P2	1.67	2.11	1.65	2.04
Debt to Recovery Ratio P3	0.96	1.20	0.78	1.47
Debt to Asset Ratio P0	0.33	0.33	0.33	0.33
Debt to Asset Ratio P1	0.33	0.33	0.33	0.33
Debt to Asset Ratio P2	0.31	0.31	0.33	0.32
Debt to Asset Ratio P3	0.33	0.31	0.34	0.32

Table 3.2. Production Management for the Risk Neutral Farmer

Risk Neutral Farmer		Whole Farm Management		Precision Agriculture	
Crop	Planting Date	Price & Int. Rate Risk	Yield Risk	Price & Int. Rate Risk	Yield Risk
Soybean P1	15-Apr	675	675	675	675
Corn P1	25-Mar	675	675	675	675
Soybean P2	15-Apr	675	600	675	600
Soybean P2	5-Jun		75		75
Corn P2	25-Mar	675	600	675	600
Corn P2	15-Apr		75		75
Soybean P3	15-Apr				525
DC Soybean P3	AP15	338	300	633	75
DC Soybean P3	5-Jun	338	38		75
DC Soybean P3	30-Jun		338		
Wheat P3	1-Oct	338	300		75
Wheat P3	15-Oct	338	338		75
Wheat P3	30-Oct		38		
Corn P3	MR25	675	675	633	675
FS-Soybean = Full Season Soybean		DC-Soybean = Double Crop Soybean with			
MR15 = March 15, AP15 = April 15, MY11 = May 11, JN05 = June 05					
OC1 = October 1st, OC15 = October 15, OC30 = October 30					
P2 = Period 2		P3 = Period 3			

Table 3.3. Economic and Financial Data for the Risk Neutral Farmer

Risk Averse Farmer	Whole Farm Management		Precision Agriculture	
	Price & Int. Rate Risk	Yield Risk	Price & Int. Rate Risk	Yield Risk
Net Worth P3 (\$)	1,288,720	1,226,815	1,299,383	1,187,147
Max Net Worth P3 (\$)	1,289,493	1,227,326	1,300,789	1,187,658
Min Net Worth P3 (\$)	1,285,216	1,202,626	1,295,004	1,166,666
Std. Dev. Net Worth P3 (\$)	1,123	3,275	1,458	3,214
C.V. Net Worth P3 (%)	0.09	0.267	0.112	0.271
Net Return P1 (\$)	148,441	148,441	148,441	148,441
Net Return P2 (\$)	115,075	66,790	118,663	64,655
Net Return P3 (\$)	55,512	52,688	75,559	65,988
Max Net Return P3 (\$)	106,702	75,609	146,373	85,683
Min Net Return P3 (\$)	-13	49,934	-2,571	62,253
Std. Dev. Net Return P3 (\$)	34,701	6,965	54,908	5,935
C.V. Net Return P3 (%)	50.86	13.22	72.67	8.99
Working Capital P3 (\$)	129,631	98,896	159,441	94,207
Debt to Recovery Ratio P1	2.71	2.71	2.71	2.71
Debt to Recovery Ratio P2	1.65	1.17	1.67	1.14
Debt to Recovery Ratio P3	0.78	0.83	0.96	0.94
Debt to Asset Ratio P1	0.33	0.33	0.33	0.33
Debt to Asset Ratio P2	0.32	0.32	0.33	0.34
Debt to Asset Ratio P3	0.34	0.35	0.35	0.37

Table 3.4. Production Management for the Risk Neutral Farmer

Risk Averse Farmer		Whole Farm Management		Precision Agriculture	
Crop	Planting Date	Price & Int. Rate Risk	Yield Risk	Price & Int. Rate Risk	Yield Risk
Soybean P1	15-Apr	675	675	675	675
Corn P1	25-Mar	675	675	675	675
Soybean P2	15-Apr	675	106	675	33
Soybean P2	5-Jun		75		75
Soybean P2	30-Jun		256		75
DC Soybean P2	15-Apr		38		161
DC Soybean P2	11-May		38		19
DC Soybean P2	5-Jun		251		19
DC Soybean P2	30-Jun				293
Wheat P2	1-Oct		38		180
Wheat P2	15-Oct		75		274
Wheat P2	30-Oct		38		38
Corn P2	25-Mar	675	653	675	590
Corn P2	11-May		58		54
Corn P2	5-Jun		52		31
Soybean P3	15-Apr			444	94
DC Soybean P3	15-Apr	195	285	12	248
DC Soybean P3	11-May		15		
DC Soybean P3	5-Jun		30		3
DC Soybean P3	30-Jun	198	345	17	329
Wheat P3	1-Oct	195	300	15	273
Wheat P3	15-Oct	198	330	15	283
Wheat P3	30-Oct		45	2	24
Corn P3	25-Mar	393	580	476	659
Corn P3	15-Apr		22		16
Corn P3	11-May		31		
Corn P3	5-Jun		42		

FS-Soybean = Full Season Soybean

DC-Soybean = Double Crop Soybean with

MR15 = March 15, AP15 = April 15, MY11 = May 11, JN05 = June 05

OC1 = October 1st, OC15 = October 15, OC30 = October 30

P2 = Period 2

P3 = Period 3

Chapter 4. Precision Agriculture Adoption, Land Degradation, and Policy Risk Analysis: The Case of Cotton Production in Benin

Introduction

Cotton production in Benin has followed a regional (West Africa) trend characterized by a double-digit production growth during the last two decades. In the late eighties, the government has made increased cotton production a key element of its economic development strategy. Considerable efforts were made to re-structure the cotton production sector and encourage production. Fertilizer, pesticide, and seeds were supplied to farmers by the government owned company at no initial cost, and reimbursed by the producer only after the crop was sold. The government also developed a network of extension specialists that provided free technical assistance and training to farmers. To encourage production, the government guaranteed a minimum seed cotton price and maintained it very stable over the years. The farm gate price received by local farmers was therefore non-correlated to world prices. As a result, production increased nine-fold from 30,400 tons in 1982 to 273,000 tons in 1994. In 2000 the production reached a record high of 362,000 tons (The World Bank).

Today, cotton production represents the backbone of Benin's economy. About one sixth of the population (about 100,000 families representing roughly 1 million people) depends on cotton production. Cotton covers 37% of the total cropped land and is cultivated in five of the six provinces in the country. The good performance achieved by the cotton sector was only made possible through government intervention that translated into an effective vertical coordination, strong research and extension systems, but also large subsidies that have helped to maintain production levels during world market prices

downturns (Boughton et al., 2003). For Benin, cotton has become the main cash crop and the largest source of export receipts and government revenues (Ousmane et al.). It represents 90% of the agricultural export, 70% of the country's total exports, and 25% of government income (The World Bank, 2002). Unfortunately, the tremendous increase in production also had adverse consequences both on the economy and the environment.

Economically, the vertical integration of the cotton production system under the control of a single company led to chronic mismanagement that forced the Benin government (under international pressure) to liberalize the entire cotton sector from cotton input distribution to cotton fiber export. Under the structural adjustment program signed between the Benin government and the World Bank, the “institutional” functions assumed by the state owned company had to be replaced by a private cotton sector management system. The company had to be dismantled and the role it plays in the organization of the sector transferred to new institutions. The institutional transition process aimed at transferring the key activities controlled by the state owned company (input distribution, ginning, and marketing) to the private sector. The gradual transition from publicly controlled activities to privately controlled ones is now however, facing real challenges, leading to a degree of uncertainty about its outcome. On the environment and production side, the rapid increase in production has not only disrupted the traditional production cycle in some regions of the country, but also has unveiled long term environmental and possibly ecological problems. There is a real need to find a production system that will at least slow the devastating impact that the new changes in the production cycle have had on the environment in the region.

This paper was a contribution not only to the PA agriculture literature but also to the economic development literature. It proposed detailed and innovative techniques for the adoption of PA that are specific to the Benin production context. The introduction of technology adoption as a possible mean to mitigate policy risk was an original way of approaching the issue of poverty reduction.

The objectives of this paper are 1) to propose a framework for precision agriculture (PA) adoption in Benin, 2) to evaluate its profitability and its impact on production decision, and 3) to analyze the impact of four possible policy outcomes on production decisions and production risk management. One of the underlying assumptions here is that the additional flexibility offered by PA could lead farmers toward a more profitable and sustainable production. To meet these objectives, a steady state crop rotation model was developed under a standard expected value variance (E-V) framework, and using mathematical programming methods.

In the remainder of this paper, a framework for the adoption of PA in Benin will be developed first. Second, the potential benefits of PA in the current production context in Benin will be discussed. Third an overview of the current political and institutional crisis threatening the future of cotton production and farmers' welfare will be provided. Finally, the mathematical programming model developed for the study will be presented followed by a description of the data, and results analysis.

Defining Precision Agriculture

A commonly accepted definition of PA is a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental

quality (Blackmore). PA, also alternately defined as Precision Farming (PF), is a decision tool that enables farmers to make better management decisions. It allows him/her to spatially and temporally micro-manage each section of the field according to its specific characteristics. The four key information technologies currently used in PF are the Global Positioning System (GPS), the geographic information system (GIS), the computer guided controller for variable rate application (VRA) of crop input and sensing technology (Swinton and Lowenberg-DeBoer, 2001).

The GPS is one of the key elements of PA and is used to determine the agricultural operator's exact geographic position in the field for operations like field mapping, soil sampling, yield monitoring or variable rate seed or nutrient application. The GIS is a software application that is designed to provide the tools to manipulate and display spatial data (Blackmore). It is a way to computerize maps, display and analyze diverse types of spatial data (soil type, ponds, fences, etc), land topography, spatial variability of soil characteristics (N, P, K, pH, compaction, etc). Many of these maps can be overlaid to look at interactions between yield and topography or yield and soil Nitrogen content for example. Agronomic, economic and environmental software models are then integrated into the GIS to produce an integrated Decision Support System (DSS).

The DSS will produce treatment maps that will show the precise type of treatment to be applied and its location in the field. Based on the producer's management decisions, VRA of various treatments is performed through a computer guided controller. The computer, connected to a self propelled spraying system, and the GPS applies in real time the required treatment according to the treatment map. Finally, remote sensing is a technology that can be used to obtain various layers of information about soil and crop

conditions. It allows detection and/or characterization of an object, series of objects, or the landscape without having the sensor in physical contact with the soil (Viacheslav et al.). It uses aerial or satellite imaging to sense crop vegetation and identify crop stresses and injuries, or pest infestation.

Environmental and Ecological problems caused by the intensive cotton production system.

In 1995 it was estimated that about 86% of African countries were showing an annual nutrient deficit greater than 30 kilograms of NPK per hectare of cropped land per year (Henoa and Baanante). This nutrient balance resulted in a widening gap between the potential and realized farm yields. In Sub-Saharan Africa (SSA) for example, annual use of NPK per hectare averaged only 10 kilograms per hectare. Fertilizer in these countries is usually used for cash crops because of their higher profitability. Even for cash crops, the fertilizers are not always applied in sufficient quantity to make up for the soil nutrient loss, causing a progressive depletion of the soil nutrients. Fertilizer and pesticide cost for cotton production in Benin, for example, represent more than 30% of the crop value and the restriction on import further reduces their availability, increasing their cost (Ton).

In addition to this preexisting problem, government incentives for cotton production created additional environmental problems. In the Borgou province (the main region for cotton production), for example, the acreage allocated to cotton production grew from 25% to 37% of total crop land between 1991 and 1997. Because of its higher profitability, farmers started to produce cotton in continuous rotation (three to four years consecutively), leading to a disruption of the traditional rotation calendar, and resulting in a faster deterioration of soil fertility. The immediate consequence has been a steady

reduction in yield. This decreased productivity pushes farmers to clear more and more forest in areas already threatened by deforestation.

All the actors involved in the sector in Benin are aware of the dangers of cotton production dynamics and cultivation techniques on the ecosystem in general and on soil fertility in particular (Ton). Though the seriousness of the situation for the long term sustainability of cotton production is recognized by both local authorities and farmers, a viable solution has yet to be found. One of the contributions of this paper is to offer a solution approach that could be implemented not only by Benin cotton producers but also by other SSA producers facing similar challenges.

Is PA technology appropriate for Benin cotton farmers?

Considerable research in the U.S., Canada, Europe and Australia have shown that PA permits a reduction in input use while maintaining the same level of yield. The majority of studies in the U.S. have also shown the adoption of PA to be profitable (Swinton and Lowenberg-DeBoer). But if this technology has primarily been developed to fit developed countries' production condition, how can it be relevant to Africa in general and to Benin in particular? For Benin and other African countries with similar production practices, a strong case can be made for the introduction of that technology in cotton production. Benin farmers, like a majority of African farmers, continue to use production practices most experts agree are not sustainable in the long term.

Economically, PA, through variable application of input, could facilitate the optimal use of fertilizers, a scarce resource in that area of the world. PA could permit an increase in yield and/or reduction in production cost, and prove to be a relevant technology for SSA farmers. Though the information technology that lies at the heart of

PA is clearly unattainable and inappropriate for most SSA farmers, the concept of using spatial information has much to offer. The components of the PA technologies to be adopted as well as the methods of adoption will need to be tailored to meet each country's production practices' constraints. To the best knowledge of the author no major study has yet been done in West Africa to test for the adaptability of PA. Research and adoption methods being used in other developing countries could, however, set an example.

In Asia, for instance, PA production concepts have been experimented with and adopted in rice and oil palm production. Dobermann et al. conducted a major field research in six countries (China, India, Indonesia, the Philippines, Thailand, and Viet Nam) on the application of site-specific nutrient management (SSNM) for intensive rice cropping. They found that the application of SSNM resulted in an average of 11% increase in yield while reducing fertilizer application by 4%. SSNM, on average, increased profitability by 12% and required little extra credit for financing its adoption. However, for some producers adopting PA resulted in net losses mainly because of the minimum care they gave to their crop. In Malaysia, remote sensing is being applied in the production of oil palm (Zainal Abidin et al.).

In Latin America, the adoption of PA techniques is also slowly growing. In Argentina, yield monitors have been installed on 1% to 2% of all combines compared to about 4% in North America (Lowenberg-DeBoer, 1999). Variable rate application (VRA), however, is unlikely to grow at this stage because of the high cost of soil sampling. It is expected that the development of PA will come through a more extensive use of lower cost technologies such as yield maps or aerial photographs. Just as Asian

and Latin American developing countries, SSA can and should also find their ways and means of adapting PA to increase agricultural productivity.

Concept of PA for Benin production practices

One of the specific goals pursued in this paper is to most efficiently apply some of the PA tools to Benin production constraints. Two types of technologies can be considered for Benin cotton growers. The first type essentially involves soil sampling and will be defined hereafter as field specific nutrient management (FSNM). The second type is referred to as precision agriculture (PA) in the remainder of the paper and involves the adoption of field mapping and within field manual variable rate application (VRA) of fertilizer.

The concept of FSNM refers to the usage of soil sampling to make management recommendations. A single soil sample is taken from a given field that would be identified by the farmer himself as an independent entity. In Northern Benin, farmers traditionally have multiple fields geographically distant (but not always) from each other by a few miles and managed individually. It would be recommended that each field be less than two hectares in size. As within soil variability increases with field size, fields larger than two hectares are likely to be more heterogeneous and may require a different management approach. Consequently, it is suggested that the adoption of FSNM should be limited to relatively smallholder farmers. Those farmers usually have an intimate knowledge of their fields and their topography. The FSNM would then be a simple fertilizer application based on field specific soil sampling. This relatively simple concept does not require the use of any computerized technology, but a nutrient application based

on fertilizer recommendation tables made available by the national agronomic research center.

The FSNM approach can also rely on the integrated farm management system developed by Benin researchers, and experimented with successfully on a small scale. The system includes the development of area maps representative of farmers' fields where they can identify roads and trees in and around their fields. They then need to get familiar with the map that serves as a basis for an integrated farm management plan. This work is somewhat similar to what is being done in Columbia and in the Philippines and described by Cook et al (2003). Participatory three-dimensional (3-D) mapping is developed using a terrain model as the basic information source, generated by the local community itself. These 3-D maps are, however, expensive to develop and are not likely to be used in Benin in the short term. The necessity of keeping a very simple field specific fertilizer application system was motivated, among other things, by the number of farmers that would need individual assistance from county agents if they had to use more complex management systems.

The necessity of developing this simple approach is also due to the fact that the adoption of any of the PA technologies, as commonly used in the US for example, will require computerized maps and advanced computer skills that virtually no farmer possesses in Benin. The FSNM approach will require just a little more assistance than these farmers are already receiving from extension agents and will largely rely on the existing agricultural research centers' expertise to deliver fertilizer application recommendations. Nationally, there may be a need to create one or two additional soil

sampling laboratories. As a result, the adoption of FSNM should be easily adaptable for Benin cotton farmers.

On the other end, the adoption of any PA technology requires the use of advanced technological and computerized tools as well as a high level of management skill that virtually no cotton producers in Benin currently possess. It is suggested that PA be used on larger farms with a size greater than five hectares. The management of within field variability through VRA technology, for example will require not only the hardware to variably apply nutrient in the field, but also a GPS, a portable computer with a PC card drive, mapping software (Gandonou et al.), and not the least, the skills to operate the hardware and software, to make maps, and to interpret them.

One of the challenges for SSA countries will be to train extension agents, many of whom are not computer literate, to use computer programs. Another challenge will be to make this type of technology widely available and at the least possible cost. Given that all crops, including cotton, in Benin are still harvested by hand and nutrients manually applied, a lot of the PA equipment commonly used in the US, VRA control system, yield monitor or spinner spreader, will not be necessary. The main equipment items required will then be a GPS receiver, a used portable computer and mapping software. Using the GPS and the mapping software, the first step will be to map the field boundaries. The fields will be divided into individual blocks and bench marks established by farmers themselves will be geo-referenced and recorded on the field map. At the end of the cropping season yields will be recorded for each block and yield maps can then be created.

A comparable site-specific technique is used in Columbia by sugar cane growers (Cook et al., 2003). The same methodology can also be used for soil sampling and mapping for larger blocks. One of the main ideas here is the way the PA concept could be implemented. Each county agent could assist two or three dozen farmers in the same village; the final management area would be the sum of all these farmers' fields. As farmers cannot directly manage the PA tools, the extension agent or production specialist would simultaneously manage a large land area and concentrate on problem areas. S/he could have access to a large pool of data based on which PA recommendations could be made within only two or three years of yield data. The analysis could be done using a simple spreadsheet and there would be no need for expensive diagnostic software. As a result, the individual cost to farmers could be relatively low.

The two proposed methods of adoption each present some advantages and some disadvantages. The main advantage of the FSNM approach is that farmers would need little or no assistance in implementing it once the soil sampling results and fertilizer application for their respective fields were made available. On the other hand, one of the disadvantages would be the absence of a map that would facilitate record keeping over time, given that one of the key components in the PA concept is the ability to analyze temporal and historical data in order to make management decisions. Another shortfall of this proposal is its high cost. Soil testing fees in Benin represent about 22% of all of the variable cost and 58% of the fertilizer cost for cotton production if the investment is depreciated in one year. The FSNM cost becomes more reasonable if we assume that soil tests are done every four years as it is a common practice in the United States. If depreciated over four years and assuming a continuous cotton rotation, FSNM only

represents an estimated 12% of total fertilizer cost. The remaining question is one of capital availability given that in Benin, all the fertilizer and pesticide used by cotton farmers is provided to them for credit, reimbursable when the crop is sold, and farmers usually do not have capital available for such investments. The cost of a soil sample can be paid for at the end of the cropping season along with the fertilizer cost if the government makes this type of credit available to farmers. The issue of cost is less problematic in the case of PA adoption because the data analysis and management recommendations are primarily based on historical yield data and not on soil tests. The investment in soil testing will be made only for problem areas previously identified by farmers themselves or with the aid of historical yield data. In that case, if the investment in soil tests is made in areas where the farmer is losing money, it should be immediately recovered. The capital requirement will also be lower given that not all of the fields will need to be sampled.

This assertion assumes that, as it is the case today, the government continues to provide extension agents with the equipment necessary to provide production assistance to cotton producers. The nature of the equipment requirement for PA adoption could also significantly slow down its adoption in areas and villages with no access to electricity. Given the nature of the current institutional structure that provides technical and production assistance to farmers, both technologies will require some level of government involvement. For the purpose of this research, adoption of FSNM was chosen for the case study because of its accessibility to most cotton producers in Banikoara.

Background on the region of study and its cropping practices

Banikoara is the largest cotton production county in Benin. It covers an area of 4,383 km² of which 49% is covered by the “W” National reserve in the north of the country. The population is estimated to be 132,000 inhabitants. Northern Benin possesses a semi-arid climate with a single rain season. Rainfall reaches approximately 900 mm annually, roughly between May and October. The rest of the year is dry and allows farmers to safely crop the cotton (cropping season lasts for up to four months) without the risk of having the fiber get wet. According to the national soil survey done in the early 1960s, the county possess some of the most suitable soil for cotton production. This comparative advantage probably explains the long tradition of cotton production in the region. The interest in cotton production during the last ten to fifteen years has significantly increased and the land area allocated to cotton production has risen by more than 128% (MAEP, 2003). This sustained increase in production was mainly motivated by a governmental policy that started supporting cotton prices and guaranteed to farmers the purchase of all of their production. This new policy has had a profound impact of the traditional cropping practices.

In Banikoara cropping activities are done both manually and with the help of animal traction. Compared to the rest of the country where most cropping activities are performed manually with rather simple tools (hoes, axes, digging bars and knives), most Banikoara farmers use animal traction. Animal traction was increasingly adopted in the region because of the continuous deterioration of the rain pattern. Days available between plowing and planting have significantly diminished making it more and more difficult to manually perform all field work during that narrow window. This, combined with

increased labor scarcity, made it necessary for most producers to adopt animal traction as their new production method. However animals are mainly used for plowing activities and not much for planting or weeding activities. New and fallow land are usually cleared by burning the field to reduce the effect of shading on crops, fertilizing the soil with litter and ashes, and reducing the sprouting of weeds, therefore easing weeding (Brüntrup,1997).

Seeding and cropping as well as fertilizer and pesticide application are also usually performed manually. Application of the appropriate rate of fertilizer, as recommended by extension agents, is based on the farmer's experience and skill. When asked if they have the technology to manually apply fertilizer dose at a variable rate in their field, farmers affirm that they are able to apply different fertilizer rate on different fields based on their experience. If the cropping practices have not evolved much over the last four decades, cropping systems have substantially changed.

Traditionally the cropping system was based on a five year rotation of sorghum at the beginning of the rotation (because farmers traditionally do not use fertilizer to produce sorghum), two years of cotton followed by corn (to benefit from the after effect of cotton fertilizer) and peanut or other leguminous crop. The fallow usually varies from 4 to 10 years, depending on the original quality of the land (Kpenavoun). The longer a field is laid fallow, the more fertile the soil becomes but the more burdensome it is to clear, whereas for shorter fallow periods less effort is required to prepare the land but the fertility will be lower and the cropping period eventually shorter. Today, farmers tend to continuously produce cotton for four to five years until complete impoverishment of the soil occurs.

A typical rotation would now be sorghum-cotton-cotton-cotton-corn-peanut. Then the land would be left for two to three fallow years in the best scenario. Changes in traditional practices were mainly motivated by increasing scarcity of land due to population pressure and the increase in land area allocated to cotton. Cotton production today represents more than 58 percent of total cropping area on average followed by corn 27 percent, sorghum, 6 percent and peanut, 3 percent representing the four major crops (Kpenavoun). One of the objectives of this research is to investigate whether or not adoption of FSNM would impact the optimum crop mix and crop rotation sequence. A potential shift away from continuous crop rotation would imply a more sustainable farm management practice. Given the current uncertainty related to the structural and institutional organization of the cotton sector, four different policy scenarios were modeled to analyze their impact on the representative farmer's optimal production strategy. Farmers in that region are particularly concerned by the ongoing transition, first because of the important role that cotton now plays in the local economy, but also because their geographic isolation could mean a relative increase in fertilizer cost due to the additional transportation cost. In the next section, a description of the policy situation and scenarios modeled will be presented.

Cotton production and institutional (political) reforms.

Until 1989, the vertically integrated cotton production system in Benin was entirely controlled by Sonapra, a state owned company. The company was the sole input distributor (seed, fertilizer, and pesticide), crop buyer, ginner, and marketer. Benefiting from a monopsony for purchasing seed cotton and from a monopoly for the sale of cotton inputs, Sonapra could sell the inputs to farmers for credit, and deduct the loan at the time

the seed cotton was purchased from farmers. The inputs were supplied to all producers at a unique price regardless of their geographical location. A minimum seed cotton price was guaranteed, and kept relatively stable in the long run. In turn, producers were obligated to sell their entire production to Sonapra, and the company committed itself to purchase all the production. In order to ensure proper functioning of the system, unauthorized input sales and cotton purchases were strictly forbidden and vigorously prosecuted by law. This integration of the cotton production sector has proven successful in encouraging farmers to increase their production. However, the company was mismanaged and had to be privatized under the Structural Adjustment Program that the government signed with international institutions.

Because cotton is of great strategic importance for public finances, the Benin government imposed a set of conditions to maintain production incentives. The private structure that would replace Sonapra should continue to guarantee a unique input price to all producers, a minimum purchase price, as well as the obligation for private ginners to purchase all the production.

To meet these requirements, new institutions made of industry stakeholders were created or strengthened to regulate the sector and meet the government constraints. They were to assume the key roles of input purchase, distribution, seed cotton collection, and transportation, or research for the creation of new seed varieties. Three main organizations play the primary roles: AIC, CSPS, and CAGIA. AIC (Association Interprofessionnelle du Coton) regroups the key stakeholders: ginners, cotton producers, and input providers' associations. This organization is the interface between the government and professional organizations. It also coordinates all other organizations'

activities. The CSPR (Centrale de Sécurisation Interprofessionnelle du coton) is a clearing house for all physical and financial transactions. It registers all input sales to farmers groups by input provider. On the output side, it registers all sales made by each farmer to cotton companies (ginners). CSPR agents are physically present in villages when inputs are delivered by input providers, and output weighed and sold to ginners. CAGIA (Coopérative d'Approvisionnement et de Gestion des Intrants Agricoles), is a cooperative of input providers in charge of managing input purchase and distribution.

Conflicts within professional organizations however erupted, leading to the creation of competing organizations, and disrupting the input distribution and seed cotton collection systems. Non-accredited input distributors sold cotton inputs to farmers without authorization and quota allocation. Some ginners, unhappy with their allocated quota, purchased seed cotton directly from farmers, bypassing CSPR. This situation led to a somewhat chaotic environment, and raised uncertainty over the outcome of the institutional transition. At this stage of the liberalization process, the government remains very involved in order to maintain a semi regulated environment. Various governmental offices and the ministry of agriculture are heavily involved in the determination of the input and farm gate seed cotton price decisions. In spite of that continuous involvement, the government is no longer playing its enforcement role as it used to, putting in jeopardy the transition process. The dissident associations members are left free to operate illegally.

The inefficiency of the new system resulted in unexpected consequences. To maximize profit, input dealers have lowered the quality of the products. As a result, productivity dropped by 20 percent after 1998 (when the input distribution reform began)

and has remained at the same level ever since. Though Benin farmers are still relatively immune from world price fluctuation because of continued government involvement, the total privatization of the sector could roll back the minimum price guarantee offered by the government. In 2001, the Benin government had to subsidize the cotton farm gate price. For countries where farmers are not shielded from world price fluctuations, a recent study has shown that the reduction in the world price from January 2001 to May 2002 by 40 percent has increased the incidence of poverty among cotton farmers from 37 percent to 59 percent (Minot and Daniels).

Four policy risk scenarios were modeled in order to evaluate farmers' ability to continue producing cotton in the wake of possible policy and institutional changes. Policy risk was defined as the prevailing uncertainty related to the current transition period. In effect, the lack of government support for the existing institutional structure and enforcement of the rules regulating the industry's stakeholder organizations could lead to the collapse of the existing system. The first policy scenario assumes a successful transition where the private sector takes total control of the cotton sector management and comply with previously described government requirements. In the second and third policy scenarios, the outcome of the institutional transition is only partially successful. In the second policy scenario, the government requirements were not fully met by the ginner's professional organizations. Ginners could refuse to be bound by a fixed purchasing price and determine the seed cotton price based on the fluctuating world cotton fiber price. Farmers would then be exposed to fluctuating cotton world prices, but input prices would remain the same. In the third scenario, farm gate cotton price remains regulated, but not input prices. As a result, Banikoara farmers, due to their geographical

isolation are likely to pay a higher input cost. In Benin, 100 percent of the fertilizer and pesticides are imported. Therefore a farmer in the north of the country would pay a higher transportation cost than those closer to the harbor in the south. Under the current system the region benefits from indirect subsidies given these farmers who do not incur the real transportation cost. Finally, the fourth scenario assumes a totally unregulated market with a fluctuating cotton price and higher input cost. The mathematical programming model utilized in the study is now discussed.

Model Specifications

In this study a mathematical programming model was used to model the production environment of a hypothetical Banikoara farmer producing cotton, corn and grain sorghum. S/he can choose either FSNM technology, or conventional technology (uniform rate application of fertilizer). It is also assumed that the farmer's objective is to maximize the expected net return.

The model is a model of crop rotation under perfect knowledge of price, yield and cost of production. The model selects the optimum crop rotations and the proportion of land resources allocated to each crop on a given soil type. Three different soil types were used to model the FSNM production method. An equilibrium known life type of model is most used to determine the optimal crop rotation that will maximize the farmer's net return above variable cost. In an equilibrium model, the farmer is assumed to be in steady-state equilibrium. This means that, once the optimum crop rotation has been determined, the same decisions are repeated in each and every future period. However, this type of model assumes that the resources available to the farmer (land, labor, capital, etc) are available in the same amount on a continuous basis and that each activity uses the

same amount of resources. Though this assumption would not always hold for labor and capital constraint, it is reasonable to assume that farmers crop the same land year after year. This approach is preferred to the disequilibrium known approach given that the farmer need not know the optimum crop rotation path over a given period of time but rather an optimum given rotation. The objective here is to depict an equilibrium one year model where the farmer adopts the same rotation practice regardless of a given weather pattern or economic condition. In this model, the rotation activities are endogenously chosen by the model.

Given that risk is a key component of a farmer's production choices, the current study relies upon the expected utility framework to analyze the production risks included in the objective function. The technique used here is known as expected value variance (E-V) analysis and was first developed by Markowitz for its application in mathematical programming. It allows an analysis of the farmer's profit maximizing production strategies under different risk aversion levels. Though sometimes criticized in the past, it has been shown to be consistent with the expected utility theory (Freund, Meyer, Markowitz). Risk is measured in term of variance of crop (or enterprise) net income. If three enterprises fall on the same mean-variance (E-V) frontier, then they are all efficient in an E-V sense, and all three producers could be rational in the sense that they maximize utility. It is accepted that the expected income is a decreasing function of the risk aversion level. That is, the more risk averse the farmer is, the lower his/her expected income will be

The general specification of the model is as followed:

Objective functions:

$$\text{Max } \bar{Y} - \Phi \sigma_Y^2$$

In this formulation, the farmer maximizes the expected average (across years) return, \bar{Y} above variable costs. Φ is the Pratt risk-aversion coefficient and σ_Y^2 is the variance of the expected annual return above variable cost.

a. Sales balance

$$- \sum_S \sum_P \sum_C \sum_{C'} \sum_F \text{YLD1}_{N,C,C',S,F} * \text{HA}_{S,P,C,C',F} + \text{SALES}_Y \leq 0 \quad \forall C, C', N$$

In this model, we have a two year crop rotation. $\text{YLD1}_{N,C,C',S}$ and $\text{YLD2}_{N,C,C',S}$ are first year and second year expected yield during year N for enterprises C and C' (first and second crop in the rotation), on soil type S. $\text{HA}_{S,P,C,C',F}$ is the number of hectares produced for enterprise C and C' on soil S under production strategy P (FSNM or conventional production) at fertilizer level F. SALES_N is the total farm sale in year N (in tone).

b. Input balance

$$\sum_S \sum_P \sum_C \sum_{C'} \sum_F \text{IREQ}_{C,F,T} \text{HA}_{S,P,C,C',F} - \text{IPURCH}_{N,T} = 0 \quad \forall T, N$$

This input purchase balance equation determines the total quantity of input used during the season by year (N) and input type (T). $\text{IPURCH}_{N,T}$ is the total quantity of input T used during the cropping season (N) and $\text{IREQ}_{C,F,T}$ is the quantity of input required per crop C, fertilizer level F and input type T.

c. Profit balance

$$\sum_P \sum_E P_C * \text{SALES}_{C,N} - \sum_P \sum_C \text{VC}_{C,P} - \sum_I \text{IP}_T * \text{IPURCH}_T - Y_N = 0 \quad \forall N$$

In the sales balance equation, it is assumed that the entire crop produced is sold by the end of the cropping season. P_C is the crop price, $\text{SALES}_{C,N}$ the quantity of seed cotton

sold, $VC_{C,P}$ stands for other variable costs, IP_T is the input cost, $IPURCH_T$ is the quantity of input purchased and Y_N is the expected net returns above variable cost (across years).

d. Land constraints

$$BASEHA_{S, N=1} = \text{inacreage}$$

$$\sum_{C'} \sum_C \sum_F \sum_P HA_{P, S, C, C', F} \leq BASEHA_{Y, S} \quad \forall N=1, S$$

$$\sum_{C'} \sum_C \sum_F \sum_P HA_{P, S, C, C', F} \leq BASEHA_{Y, S} \quad \forall N+1, S$$

The first equation fixes the amount of land that was planted the first year by soil type. The second sets up the initial acres in year one as the available land for that year. Finally the last equation, $BASEHA$, is the total number of acres available to the farmer.

e. Land ratio constraints

$$BASEHA_{N, S'} * HA_{FSP} - BASEHA_S * HA_{FS'P} = 0 \quad \forall P, F, S \neq S'$$

$$BASEHA_{N, S'} * \sum_E HA_{FSP} - INHA_S * \sum_E HA_{FS'P} = 0 \quad \forall P, F, S \neq S'$$

These two equations control for the non-variable rate management strategy under conventional production practices for the first equation, and FSNM for the second.

Summary of indices:

- C represents the different enterprises or crops (corn, wheat and soybeans)
- P is the input management strategy (single or variable rate application)
- S represents the three soil types (bani1, bani2 or bani3)
- F is the fertilizer application level (low or medium)
- T is the type of input used (fertilizer or pesticide)
- N is the number of years

Data

Data required in the development of the mathematical programming model includes simulated soil specific crop yields, variable production costs, and crops' output and input prices. Most of the data used was collected during a field trip in Benin in August and September 2003.

Crops yields were obtained using WinEpic, an interface to EPIC (Erosion-Productivity Impact Calculator). In addition to being an erosion impact calculator, EPIC is also a crop growth simulation model (Appendix 2). Crop growth simulation models are capable of simulating crop variables and management practices such as plant population, planting and harvesting dates, maturity groups, irrigation, drainage systems, tillage, irrigation methods, etc. Compared to other crop growth models, EPIC has the capability to simulate yield data when fertilizer levels are varied. WinEpic adds to EPIC a Windows interface, economic data and production practice environment familiar to economists. The EPIC model was calibrated to fit Banikoara production conditions. Historical weather and soil database were created and incorporated in EPIC. Fertilizer application rate as well as sowing date data were incorporated into the model in order to replicate the production environment of a typical crop grower in Banikoara. The weather and soil data were obtained from INRAB (Institut National de Recherche Agricole du Bénin). Typical recommendations for planting dates, types, quantity, time and frequency of chemical and fertilizer use were obtained from a survey of local farmers and extension agents.

The model generates expected yields for corn, cotton and sorghum for varying fertilizer levels (nitrogen and phosphorus), and traditional planting dates. Two fertilizer levels were used to generate three series of yield data on three types of soil. The first soil is silt-loamy soil, the second a clay-loamy soil and the third soil a silt soil. For historical

reasons most farming units have two to six different fields often in different geographic areas. The medium fertilization level corresponds to the exact recommendations made to farmers by county agents. Yield data using a low level of fertilizer application was also generated because of common practices of application of lower than recommended levels of fertilizer. Crop yields were validated using Banikoara field trial results provided by the agricultural research center (CRA-CF) as well as individual farmers' yield data gathered through the survey.

The Model does a reasonable job of simulating corn, cotton and sorghum yields. Yields data are in the range of the field trial yield obtained in Banikoara. However, these yields are much higher than county average yields. The county average yield includes all types of soils, production practices and most important varieties of corn and sorghum. For corn production, for example, in spite of the wide availability of high yielding corn seed, farmers continue to devote relatively large land areas to the production of traditional low yield crops for domestic consumption. As a result, for a six year county average yield for corn of 1640 kg/ha, EPIC simulated 2831 kg/ha which is closer to yields commonly obtained by producers using commercial seeds and some chemical fertilizer. Historical field trial data were, however, not available to compare the variance with the ones obtained with EPIC. Yield simulations also show lower crop yields for the second year in the rotation.

Production budgets were created for each crop to obtain variable production costs. Data were obtained through farmers' surveys, personal communication from county agents and also from Adégbidi. Based on production practices and the farm size model in the study, only selected labor costs were incorporated in the budgets. Farm gate output

and input prices were collected from the Ministry of agriculture. The last ten years corn, cotton, and sorghum prices were utilized to model marketing risk. Farm gate cotton price modeled in policy scenario two and four were estimated by subtracting total cotton fiber ginning and processing cost (Waddell et al.) from world price (Cotlook, Ltd). Finally, precision agriculture cost was estimated based on the FSNM production approach. The scenario assumes a trained county agent in charge of forty farmers. FSNM adoption cost includes the agent's annual income, and the cost of four soil samples amortized over four years.

Results and analysis

The current model depicts the production environment of a typical Banikoara cotton farmer. Two models were run for each of the four policy scenarios. In the first model the farmer uses traditional uniform rate nutrients on each of his/her fields and in the second model he can apply low or medium fertilizer rate on each of his three fields. Results from the two models are compared and analyzed for each policy scenario in order to evaluate the profitability of the FSNM technology as well as the impact of each policy option on the farmer's optimal production strategy. Model statistics results and optimal crop mix and rotation are presented by policy scenario for different risk aversion levels.

In the first policy scenario (low risk) (table 1), it was assumed a smooth institutional transition based on governmental requirements and guidelines for the minimum seed cotton price or maximum fertilizer and pesticide price. In that scenario, the net return above variable costs for the risk neutral farmer producing under conventional production practices was \$3,580. This figure may appear high for the hypothetical Benin cotton farmer producing 7 hectares, but it also includes the value of

family labor and all fixed equipment costs (plowing equipment, animal purchase and maintenance cost as well as all small equipments cost). The net return as modeled also assumes that the farmer sells all his production at market value. In reality, a large portion of the corn and the sorghum (when it is produced) is kept for the large family consumption. The optimal crop rotation for the risk neutral farmer was corn and cotton produced using medium level of fertilizer application. As risk aversion increases however, the farmer's production strategy changes as well.

The medium risk averse producer could obtain a net return of \$2,372 with a maximum attainable return of \$5,622 and a c.v. of 46 percent. That farmer allocates 57 percent of his available land to the production of continuous cotton with a low rate of fertilizer application, and his income is only 66 percent of that of the risk neutral producer. The acreage allocated to continuous cotton rotation increases as risk aversion increases. This production strategy was also found to be a common practice in the region. All the farmers surveyed adopting this risk aversion strategy and representing the majority of farmers surveyed, are fully aware of the financial penalty associated with their risk aversion behavior and production decisions. Producing cotton in continuous rotation in spite of the financial and ecological penalty is motivated by aversion to income variability, but not only that. By producing cotton, farmers are guaranteed to have their production sold, and the money received as a lump sum. In his thesis, Bradley found (out of 101 farmers interviewed) that 73.3 percent of farmers viewed cotton as the most important crop for the family; 5 percent choose corn, 18.8 percent sorghum/millet and 3 percent peanuts. He also found that cotton remains, for farmers, a very important crop, even with regard to food security, because it is the only crop with an organized market.

99 percent of interviewed farmers say that they would be interested in alternative crops. Selling corn or sorghum involves long trips to local or regional markets while exposing the farmer to full marketing risk. In addition, the crop is sold over a longer time period with the money coming in smaller increments, making it, for them, more difficult to save and make important investments. Finally, there is a social recognition that comes with the quantity of cotton sold.

Results here show that variable rate fertilizer application results in an increased yield. However, given the relatively high cost of adoption for local conditions and income, net returns associated with FSNM adoption was lower than one of conventional practices. For the risk neutral FSNM adaptor, net return was \$3,457, only 4 percent lower than the return in the conventional case. Therefore, limited governmental support would render FSNM profitable. This result can also in part be explained by the fact that there are only two levels of nutrient application rate in the model allowing for less flexibility. FSNM would also have been more profitable under a different set of assumptions. The very conservative approach used here included the FSNM service provider income in the technology cost. The difference in the expected net return between FSNM and traditional production practice narrows as risk aversion increases. However, FSNM adoption slightly increases income risk as it results in a higher c.v. compared to uniform rate fertilizer application.

Production strategies for FSNM were different from the ones obtained with conventional practices for risk averse farmers, but identical for risk neutral ones. These differences are important in the sense that adoption of PA allows the farmer to diversify. First, the proportion of available land area allocated to continuous cotton production (75

percent) was smaller than in the conventional case (78 percent). Usage of a higher level of fertilizer application not only is more profitable, exception being made of the technology cost, but also will be likely to reduce the incidence of soil depletion and, ultimately, the need for farmers to move away from their villages in search of new land.

In the second policy scenario (marketing risk), in addition to the corn and sorghum marketing risk, farmers are now faced with cotton marketing risk. Results in table 2 show that in such a scenario, the expected net return substantially decreases compared to the previous scenario (low risk) across all risk aversion levels. When exposed to the cotton marketing risk, the risk neutral producer could only expect a net return of \$3,514, a 3 percent decrease compared to the case where prices are more stable. Though this gap decreases as risk aversion increases to reach only 14 percent for the extreme risk averse farmer, the c.v. in this second scenario (marketing risk) is twice that of the previous scenario (low risk). Namely, even extreme risk aversion producers still have to sustain a relatively high level of risk when the cotton price is not guaranteed and stable. This exposure to risk comes essentially from the production of corn and sorghum as cotton is no longer part of the optimum rotation strategy. Cotton price fluctuation forces high and extreme risk averse producers to renounce its production. Even the medium risk averse farmer allocates only 0.07 ha to cotton in rotation with corn. This comparative result also could help explain the high interest of risk averse farmers in cotton production when prices are stable, given that the introduction of cotton in their optimum production strategy could reduce by half their exposure to income risk. Only the risk neutral producer continued to allocate most of his available land to corn-cotton

rotation. The low risk aversion farmer had already dropped the land area allocated to corn-cotton rotation to only 2.24 ha.

In the case of variable rate fertilizer application, FSNM enabled the risk neutral producer to increase his expected net return by \$926 compared to the conventional production practice. This higher expected mean return was primarily driven by the maximum attainable net return above variable costs of \$35,529 compared to only \$13,734 in the case of conventional practice. On a year to year basis, it appears that the FSNM practice enables the farmer to better adapt to cotton price variability and take full advantage of opportunities in good years. For risk averse producers however, the high technology cost still slightly outweighs the monetary benefit of adoption. The difference for the low risk averse producer however is small enough (3 percent) to be considered negligible. There were no major differences in the optimal crop mix and rotation between the two production methods in this scenario.

Given the social environment where farmers are largely risk averse, exposure to cotton price risk could well lead to a substantial drop in cotton acreage in the region. Nonetheless, consideration should be made of factors not modeled here. For example, the guarantee of a lump sum payment of their production is likely to continue to allure even the most risk averse farmers.

In the third policy scenario (table3), an increase in fertilizer and pesticide cost was simulated. Cotton is a fertilizer and pesticide intensive crop, and the prospect of the impact of an increase in input price on its profitability was important to analyze. In the hypothesis of an increase in fertilizer price, the major change in the optimal solution was a shift from cotton to sorghum production in rotation with corn for the risk neutral

producer. This shift could be explained by the low level of fertilizer used for sorghum production compared to cotton. Because of the relatively high price of input needed for cotton production, cotton was no longer a profitable alternative for the risk neutral farmer. The removal of cotton production from the optimal crop mix rotation did not noticeably impact net return. Expected net return above variable cost for the risk neutral farmer dropped 5 percent to \$3,389 compared to the first scenario (low risk). For risk averse farmers however, cotton production remained an optimum production strategy. For the medium risk averse producer for example, the increase in input price resulted in a 9 percent drop in net return compared to the first scenario (low risk). The optimal crop mix and land allocation for the conventional and FSNM production practices were almost identical.

The last policy scenario simulates the environment where the institutional transition process failed. As anticipated, the expected returns were the lowest of all four scenarios across risk aversion levels in the case of the conventional production practice. Expected net return for the risk neutral farmer was \$3,372. Because of the fluctuating cotton price, the c.v. was high for risk averse farmers. The low risk averse producer could expect a net return of \$2,472 with an associated c.v. of 95 percent. The results for FSNM adoption are similar to the ones obtained in previous scenarios (low risk and marketing risk) with lower expected net returns and higher risk.

On the production side, the optimum crop mix and rotation was not expected. For the risk neutral farmer, cotton in rotation with corn was again part of the optimal production strategy. When faced with higher input costs, the risk neutral producer dropped cotton, replacing it with sorghum. Though it was already found that seed cotton

price fluctuation did not affect the risk neutral producer strategy, it was expected that, as in the previous scenario (increased in fertilizer and pesticide cost), the increase in input cost would also have removed cotton production from the optimal solution. Inversely, risk neutral producers reacted as they did when faced with increased marketing risk by replacing cotton with sorghum in rotation with corn. So, when faced with both the marketing risk and higher input cost for cotton, the risk neutral farmer was found to be more sensitive to the opportunities in the price variability while risk averse farmers reacted more to the increase in input cost.

Conclusion

From this study it can be concluded that PA could indeed be adopted by most of Benin cotton producers but the adoption of such a technology will require some level of government involvement. Though not more profitable than uniform rate application, FSNM increased yield and production. However, there is not a difference in net results between VRA and conventional production, signaling that the gain in increased yield was almost entirely absorbed by the technology cost. In the case of limited government involvement through a full of partial support of county agents, the adoption of the new technology will prove profitable and increase farmers' disposal income. In addition, FSNM adoption through increased fertilizer use at an optimum level could help reduce soil depletion. Technology cost and availability of qualified personnel will remain an obstacle to adoption in Benin.

At the production level, FSNM has no major impact on the production strategy adopted by risk neutral farmers. The adoption of PA did not change the crop rotation strategy adopted by farmers. Cotton remains in the rotation in almost all scenarios for the

risk neutral farmer but was never produced in continuous rotation, indicating that the observed phenomenon of continuous cotton production is mainly the fact of risk averse farmers. Assuming, therefore, that the vast majority of farmers are risk averse, a failed institutional transition could lead to a complete collapse of cotton production in the region. An increase in fertilizer cost, however, has more impact on risk averse farmers' ability to continue to produce cotton than unstable cotton prices would have.

Table 4.1. Policy Scenario 1: no policy change

Policy1: Uniform rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$3,580	\$3,398	\$2,372	\$2,147	\$2,021		
Max (\$)	\$15,959	\$11,620	\$5,622	\$3,900	\$3,223		
Min (\$)	-\$527	-\$519	\$570	\$576	\$586		
Std. Dev (\$)	\$3,552	\$3,078	\$1,104	\$769	\$612		
C.V. (%)	99.2	90.6	46.5	35.8	30.3		
Policy1: Variable rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$3,457	\$3,249	\$2,332	\$2,097	\$1,970		
Max (\$)	\$15,835	\$11,381	\$5,249	\$4,226	\$3,183		
Min (\$)	-\$650	-\$300	\$473	\$490	\$482		
Std. Dev (\$)	\$3,552	\$2,778	\$1,92	\$831	\$639		
C.V. (%)	102.8	85.5	48.1	39.1	32.4		
Policy1: Uniform rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
cotton	cotton	low			4.11	5.02	5.47
cotton	cotton	med					
cotton	sorghum	med			0.79	0.62	0.55
corn	cotton	med	7.00	6.95	2.10	1.36	0.98
corn	sorghum	low		0.05			
Policy1: Variable rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
cotton	cotton	low			2.72	3.33	3.63
cotton	cotton	med			1.09	1.33	1.61
cotton	sorghum	med		0.28	0.76	0.69	0.59
corn	cotton	low		2.66	1.04	0.71	0.50
corn	cotton	med	7.00	3.55	1.39	0.95	0.67
corn	sorghum	low		0.52			

Neutral = 50% of risk significance level
Low = 55% of risk significance level

Medium = 70% of risk significance level
High = 80% of risk significance level
Extreme = 90% of risk significance level

Table 4.2. Policy scenario 2: cotton marketing risk

Policy2: Uniform rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$2,514	\$2,500	\$2,043	\$1,944	\$1,730		
Max (\$)	\$13,734	\$12,700	\$6,623	\$5,575	\$4,568		
Min (\$)	-\$1,020	\$42	\$228	\$159	\$170		
Std. Dev (\$)	\$3,829	\$2,346	\$1,292	\$1,188	\$1,028		
C.V. (%)	152.3	93.9	63.2	61.1	59.4		
Policy2: Variable rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$3,441	\$2,436	\$1,932	\$1,852	\$1,607		
Max (\$)	\$35,529	\$13,108	\$6,587	\$5,912	\$4,454		
Min (\$)	-\$1,213	-\$96	\$153	\$36	\$47		
Std. Dev (\$)	\$5,712	\$2,444	\$1,305	\$1,218	\$1,028		
C.V. (%)	166.0	100.3	67.6	65.8	64.0		
Policy2: Uniform rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
corn	cotton	med	6.72	2.24	0.14		
corn	sorghum	low	0.28	4.76	6.86	7.00	6.41
sorghum	sorghum	med					0.59
Policy2: Variable rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
corn	cotton	low		1.14	0.09		
corn	cotton	med	7.00	1.52	0.13		
corn	sorghum	low		4.34	6.78	7.00	6.41
sorghum	sorghum	med					0.59

Neutral = 50% of risk significance level
 Low = 55% of risk significance level

Medium = 70% of risk significance level
 High = 80% of risk significance level
 Extreme = 90% of risk significance level

Table 4.3. Policy scenario 3: input price increase

Policy3: Uniform rate application of fertilizer						
Risk Aversion	Neutral	Low	Medium	High	Extreme	
Mean (\$)	\$3,389	\$3,198	\$2,166	\$1,967	\$1,844	
Max (\$)	\$58,508	\$11,723	\$5,292	\$3,782	\$3,114	
Min (\$)	-\$184	-\$393	\$416	\$402	\$416	
Std. Dev (\$)	\$7,136	\$2,929	\$1,067	\$768	\$615	
C.V. (%)	210.6	91.6	49.3	39.1	33.4	

Policy3: Variable rate application of fertilizer						
Risk Aversion	Neutral	Low	Medium	High	Extreme	
Mean (\$)	\$3,266	\$3,109	\$2,203	\$1,945	\$1,785	
Max (\$)	\$58,385	\$11,240	\$5,804	\$3,972	\$3,136	
Min (\$)	-\$308	-\$498	\$314	\$313	\$321	
Std. Dev (\$)	\$7,136	\$2,834	\$1,206	\$832	\$637	
C.V. (%)	218.5	91.2	54.7	42.8	35.7	

1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
cotton	cotton	low			3.74	4.97	5.40
cotton	sorghum	med		0.51	0.96	0.61	0.56
corn	cotton	low					
corn	cotton	med		5.75	2.26	1.35	0.97
corn	sorghum	low		0.74			
corn	sorghum	med	7.00				
sorghum	sorghum	med			0.05	0.07	0.07

Policy3: Variable rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
cotton	cotton	low			2.26	3.26	3.36
cotton	cotton	med			0.90	1.30	1.34
cotton	sorghum	low				0.00	0.16
cotton	sorghum	med		0.06	1.15	0.73	0.73
corn	cotton	low		2.63	1.15	0.73	0.60
corn	cotton	med		3.50	1.54	0.97	0.80
corn	sorghum	low		0.81			
corn	sorghum	med	7.00				

Neutral = 50% of risk significance level
Low = 55% of risk significance level

Medium = 70% of risk significance level
High = 80% of risk significance level
Extreme = 90% of risk significance level

Table 4.4 Policy scenario 4: cotton marketing risk and input price increase

Policy4: Uniform rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$3,372	\$2,432	\$1,956	\$1,943	\$1,943		
Max (\$)	\$35,461	\$14,316	\$6,698	\$6,698	\$6,698		
Min (\$)	-\$1,281	-\$97	\$120	\$79	\$79		
Std. Dev (\$)	\$5,712	\$2,496	\$1,286	\$1,269	\$1,269		
C.V. (%)	164.9	95.3	65.4	63.8	61.8		
Policy4: Variable rate application of fertilizer							
Risk Aversion	Neutral	Low	Medium	High	Extreme		
Mean (\$)	\$3,302	\$2,723	\$1,891	\$1,788	\$1,517		
Max (\$)	\$35,390	\$21,064	\$6,531	\$5,384	\$4,270		
Min (\$)	-\$1,351	-\$1,056	\$83	\$8	\$43		
Std. Dev (\$)	\$5,712	\$4,086	\$1,291	\$1,184	\$981		
C.V. (%)	173.0	150.1	68.3	66.2	64.7		
Policy4: Uniform rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
corn	cotton	med	7.00	2.38	0.08		
corn	sorghum	low		4.62	6.92	7.00	7.00
Policy4: Variable rate application of fertilizer							
1st Crop Rotation	2nd Crop Rotation	Fertilizer Rate	Risk Aversion Level				
			Neutral	Low	Medium	High	Extreme
corn	cotton	low		5.19	0.06		
corn	cotton	med	7.00	1.81	0.08		
corn	sorghum	low			6.85	7.00	5.59
sorghum	sorghum	med					

Neutral = 50% of risk significance level
Low = 55% of risk significance level

Medium = 70% of risk significance level
High = 80% of risk significance level
Extreme = 90% of risk significance level

Chapter 5. Conclusion

This dissertation can be divided in two parts. The first part was aimed at studying the impact of precision agriculture (PA) technology adoption on a Kentucky grain farmer's production and financial risk management. It contributes to the agricultural economic literature in general and to the PA literature in particular in many ways. It is the first comprehensible research that uses soil specific historical simulated crop yield data to model the profitability of PA and its impact on production risk management. By comparing PA to another production risk reducing technology, subsurface drip irrigation (SDI), it puts into perspective the relative importance of PA as a risk reducing technology. Methodologically, it is also the first paper to use a discrete stochastic sequential programming (DSSP) model to analyze the impact of technology adoption on the farm's financial risk. The model developed here displays a unique and innovative application of DSSP in financial risk analysis. By extending its scope above the sole analysis of profitability of new technologies, this research shows that the most profitable combination is not financially affordable.

In the second part of the dissertation a framework was developed for PA adoption in Benin for a small hold seed cotton producer. This part of the dissertation was a contribution not only to the PA agriculture literature but also to the economic development literature. It proposed detailed and innovative techniques for the adoption of PA that are specific to the Benin production context. The introduction of technology adoption as a possible mean to mitigate policy risk was an original way of approaching the issue of poverty reduction. The remaining of this chapter will summarize the key findings and different scenarios used in each chapter and identify some of the shortfall of this research.

The introductory chapter attempted to provide a general definition of precision agriculture technology. The type of PA technology used in the study was also specified, and the link between PA and risk management were presented. Then, the study's objectives and general structure were outlined.

In the second chapter seven different production scenarios were presented to analyze the profitability of PA and SDI technologies in the case of the risk neutral farmer, as well as their risk management potential at various risk aversion levels. The first scenario (WFM) is the base case scenario where no investment is made. In the second scenario (PA), the producer invests in PA equipment and adopts a variable rate production management method. In the third scenario (SDI-full), an investment in irrigation equipment was made and all the available production area irrigated. The fourth scenario (SDI-opt) is the combination of scenarios two and three whereas in the fifth scenario (PA/SDI) irrigation was applied only when it was optimum. Finally, scenarios six (CH-PA) and seven (CH-PA/SDI) were the replica of scenarios two and five with custom hiring of the PA service. The production environment of a representative Henderson County commercial grain farmer was modeled using mathematical programming techniques.

The results show that for the risk neutral producer, scenario seven (CH-PA/SDI) was the most profitable followed by scenarios four (SDI-opt) and scenario five (PA/SDI). For a farmer Adoption of the PA technology alone, whether through investment in the technology or custom hiring of the service, was less profitable than in the base scenario (WFM). For the risk neutral farmer, the lowest income variability was obtained when the entire cropping area was irrigated. Adoption of PA however slightly increased the

production risk. In all scenarios, production risk was generally managed through an extension of the planting window.

If a simultaneous investment in PA and SDI equipment is most profitable, it may not be financially feasible. In the third chapter, the production model was modified and extended to include additional financial risks that the producer is exposed to once the investment decision is made. A discrete stochastic sequential programming (DSSP) model was used to model the price and short term interest rate risk over three production periods. Production risk was also modeled using the same modeling framework. The objective function was to maximize the farm net worth at the end of the third period. An investment in irrigation never entered the optimal solution in any of these two models. In a financial risk environment, results show that an investment in PA technology increased the farm's ending net worth. On the other hand, ending net worth decreases in the yield risk scenario. Expected net returns should not be compared to the ones obtained in the production risk chapter, as different states of nature were modeled. The investment in PA equipment in most scenarios worsens the farm's financial situation but still enables the farm manager to continue to meet his/her financial obligations. The negative results of the PA investment on the production risk models results, in part, from the assumptions made in the definition of PA technology.

Although they give a good indication of the farmer's optimum production practices and risk management decisions, based on weather and yield variability, these results should, however, be taken with caution. If the cost and associated benefits of SDI were accurately modeled, those of PA were not. By only modeling variable rate fertilizer application for PA, only a partial benefit of the PA technology was considered, while its

full cost was allocated. The potential financial benefits of PA lay far beyond what has been modeled here and have not been modeled. Most farmers would not consider an investment in PA with the single objective of using it for variable rate fertilizer application. A higher financial gain could be obtained when the PA equipment is used for variable rate lime application as well. Lowenberg-DeBoer (2000) reports, for example, that “many farmers in Indiana use VRA lime, but not VRA NPK” (p. 247). Variable rate application of lime was not considered in these models because of the limitations of the biophysical model used.

Lime application was not, however, a concern in the last chapter of the dissertation because lime is generally not used for farming in Benin. In that chapter the production environment of a Northern Benin cotton farmer was modeled. A framework for the adoption of precision agriculture defined as field specific management (FSM) was proposed. Given the high cost of the fertilizer input used in cotton production and the potential of FSM to reduce input application, four different policy scenarios were modeled to analyze the impact of seed cotton and input price change on the profitability of PA. The cotton production sector in Benin is characterized by an uncertainty related to ongoing institutional changes that could affect the future of cotton production in Benin. The first scenario is the base case scenario where the current production incentives remain the same. In the second scenario farmers lose the benefit of a stable and guaranteed seed cotton price and are exposed to the fluctuating world price. In the third scenario, the seed cotton price remains stable but the input price increases. Finally, the fourth scenario was a combination of the last two scenarios.

The results show that, for the risk neutral producer, an adoption of the FSM technology would be more profitable than continuing to produce using current production techniques, if the farmer was exposed to seed cotton marketing risk. In all other cases the change in production technique reduced the farmer's expected net return. For risk averse producers the adoption of the FSM production method generally increases production risk and also reduces expected net return. This model also has its limitations as only a two year crop rotation and three soil types were modeled. More variability could have increased the profitability of FSM.

A few general conclusions can be derived from this research. 1) For a farmer selectively investing in and installing the irrigation equipment where it is the most needed in his/her field, custom hiring the PA service could be a great opportunity to increase the operation's profitability. Investing in the PA equipment alone or custom hiring the service did not increase the farm operation's profitability; neither did it reduce the production risk. For this hypothetical Kentucky grain farmer, irrigating the entire cropping area resulted in a substantial reduction in the expected net return. 2) When the farmer is faced with crop price and short term interest rate risk (defined here as financial risk) the impact on the farm operation's financial indicators was somewhat different for the risk neutral and for the risk averse farmer. For the risk neutral farmer the working capital needed to run the farm's daily operations was lower than in the situation where the investment had not been made and the debt to asset ratio was higher in the third period. For the risk averse farmer the investment increased the expected net returns and the net worth and improved the debt to recovery ratio. The debt to asset ratio was, however, increased by one percentage point. 3) For a Benin cotton producer the adoption of the field specific

nutrient management (FSNM) production technique was not profitable, mainly due to the high cost of the technology. Though the adoption of the new technology increased yield, there was no difference in production strategies (crop rotation) between traditional production practices and the FSNM production practice. Therefore, the adoption of the new technology would not change current production practices and therefore would not help improve the environmental crisis on the long run. Finally, the failure of a successful institutional transition will not only reduce farmer's income and increase their exposure to price and production risk, risk averse farmers will also substantially reduce or stop the production of seed cotton.

Appendix:

Appendix 1. Expected Utility Framework

A number of studies have offered different methods for evaluating farmers' risk aversion level and decision making under uncertainty (Binswanger, Dillon and Scandizzo, Antle, Anderson et al. Freund, Hardaker et al.). This study uses a mathematical programming model to "capture" the risk inherent in the farmer's decision-making process.

One of the advantages of using mathematical programming risk models is their ability to depict the risk inherent in model parameters. An important assumption made in many programming formulations involves the potential decision maker's reaction to risk. The most fundamental decision that exists among those models is between cases where:

1. all decisions are made today and the uncertain outcome is known only after all random draws from the distribution have been taken; 2. decisions are made sequentially (step by step) as uncertainties are resolved. The first type of model is commonly called stochastic programming and the second one, originally developed by Dantzig, is classified as stochastic programming with a resource model. Stochastic programming models usually treat risk in the objective function coefficients, technical coefficients or right hand sides (RHS) separately or collectively (McCarl and Spreen).

In these three chapters the first type of model, stochastic programming, was be utilized. The technique used here is known as expected value variance (E-V) analysis and was first developed by Markowitz and Freund for its application in mathematical programming. It allows an analysis of the farmer's profit maximizing production strategies under different risk aversion levels. The risk parameter is incorporated in the

objective function, assuming that the parameter's probability distribution is known with certainty. Though highly criticized in the past, it has been shown to be consistent with the expected utility theory.

The expected utility theorem is one of the most established decision theories in the economic literature. The expected utility model usually assumes that the utility function is quadratic and that profits are normally distributed. It views decision making under risk as a choice between alternatives (Pennings et al.), and provides a single-valued index that orders action choices according to the preferences or attitudes of the decision maker (Robinson et al.). Given any two farm plans for example X_1 and X_2 , the theory predicts X_1 will be preferred to X_2 only if $E[U(Y_1)] > E[U(Y_2)]$, where E denotes the expected value and Y the income level. That is, X_1 is preferred to X_2 if the expected, or average, value of utility over all possible income outcomes is larger for X_1 than X_2 . (Hazell and Norton).

In a whole farm planning context under risk, the three basic assumptions in the expected value-variance (E-V) approach are ones where 1. risk is considered only in relation to each activity's expected gross margin Y , with non-stochastic constraints; 2. the farm manager's utility function is assumed to be quadratic, or exponential over a multivariate normal distributed set of expected gross margins for all activities; and 3. risk is insignificant with respect to wealth (Tsiang, 1972).

Let us assume that the farmer's utility function is best described by the following quadratic function:

$$U(Y) = \alpha Y + \beta Y^2$$

where σ and β are constants. After derivation, the relevant decision rule for ranking a risky farm plan for the farmer becomes

$$E[U(Y)] = \sigma E[Y] + \beta V[Y] + \beta E[Y]^2$$

where $V[Y]$ denotes the variance of Y . By this rule, the farmer should rank farm plans solely in terms of their expected (mean) income $E[Y]$ and their variance of income $v[Y]$. Given that mean and variance of income are the only parameters relevant to his risky choice, the farmer's objective will be to allocate a fixed amount of scarce land resource among n risky crop production activities, X_j . If $\sigma > 0$ and $\beta < 0$, then the farmer will prefer plans having higher expected income and lower variances of income. The problem is then to find a set of values X_j that maximizes his utility function.

The E-V efficient set of farm plans can then be derived with the aid of quadratic programming and be algebraically expressed by the following equations:

$$E = \sum_j c_j X_j \text{ is the activity expected gross margin}$$

$$V = \sum_j \sum_k s_{jk} X_j X_k \text{ is the variance of activity gross margin.}$$

X_j is the level of the j^{th} farm activity, c_j is the gross margin per unit of j^{th} farm activity, s_{jk} is the covariance of gross margins between the j^{th} and the k^{th} activity.

For a risk averse farmer, the quadratic utility function will be of the form:

$$U = E + bE^2 + bV ; b \geq 0$$

where b is the risk aversion coefficient. Substitution of the above expression for E and V into U gives the following quadratic utility function

$$U = \sum_j c_j X_j + b \left(\sum_j c_j X_j \right)^2 + b \sum_j \sum_k s_{jk} X_j X_k$$

The objective of the E-V approach is to generate the so-called efficient frontier and then to select an optimal farm from the set of efficient risky production activities, which maximizes the farm manager's utility. To obtain the efficient E-V frontier, the variance of activities V , is minimized for each level of expected income E , while retaining feasibility with respect to the available resource constraints. An empirical description of the model is presented in the following section.

Appendix 2. EPIC historical information and calibration procedure.

The components of the model can be placed into nine major divisions: hydrology (surface runoff, percolation, evapotranspiration), weather (precipitation, air temperature and solar radiation, wind and relative humidity), erosion (water and wind), nutrients (nitrogen (N) and phosphorus (P)), soil temperature, crop growth model, tillage, plant environment control (drainage, irrigation, fertilization, lime and pesticide) and economics. The current version of the model can produce indicators such as nutrient loss from fertilizer and animal manure application (Edwards et al., Phillips et al.), climate change impact on crop yield and soil erosion (Favis-Mortlock et al., Stockle et al., Williams et al., 1996), losses from field application of pesticides (Williams et al., 1992), and soil C sequestration as a function of cropping and management systems (Mitchell et al.). The flexibility of the model has led to its adoption within the Resource and Agricultural Policy System (RAPS), an integrated modeling system designed to project shifts in production practices (crop rotation, tillage levels, and conservation practices) and evaluate the resulting environmental impact, in response to agricultural policies implemented for the North Central USA (Badcock et al.).

EPIC was also tested and validated in many different ways, and several of its components were tested and reported in the literature. Williams and Renard showed that EPIC performed well in predicting crop yields and runoff in humid regions. Steiner et al. found that EPIC performance in simulating the water balance of a wheat-sorghum-fallow rotation under semiarid conditions was generally satisfactory. Bryant et al. also used EPIC to simulate corn yield response to irrigation timing and found that the model was able to predict up to 86% of the variance in actual yields for three years of measured data.

Watkins et al. used EPIC to evaluate the environmental feasibility of variable rate nitrogen fertilizer with carry-over effect.

EPIC here was calibrated so as to replicate the production environment in Henderson. The county historical daily weather and soil database were used for the simulation. Weather and soil databases were made available by the Blackland Extension and Research Center in Temple, TX. The primary objective of the calibration process is to ensure that the yields generated by the model were not significantly too high or too low compared to county average yield, for example. Two components of the model, heat unit and maximum annual irrigation water applied, were adjusted for each crop in order to replicate Kentucky weather conditions. Heat units (thermal time) are used to estimate the rate of crop development, and the fraction of crop maturity in a specific day is expressed as the number of heat units that have been accumulated to that day divided by the number of heat units required for crop maturity (Mitchell et al.). Maximum available water also needed to be adjusted and limited to the average rainfall level in Kentucky. After the calibration stage, the model needed to be validated.

Appendix 3. Henderson County selected soil characteristics.

The Loring-Grenada association is made of brown and well-drained soils and is well suited for farming. Memphis, which represents 10% of the association is also a well-drained and brown soil. “Loring soils make up to 35 percent of the association, Grenada soils 20 percent, Memphis soils 15 percent and other soils make up the rest” (Henderson County soil survey). The Memphis-Wakeland association is made of brown, strongly sloping to steep, dominantly well-drained and silty soils. Memphis makes up more than 60% of that association. Huntington, a very deep, well drained, and moderately permeable soil also found in the region, was added to the soil selection. It is a silt loam soil, on a 2 percent slope. This fifth soil was added on the previously described four soils on the assumption that farmers often own or rent land in different geographical locations.

Each soil has various characteristics and slopes. In the Loring-Grenada series, the Grenada silt loam 2 to 6 percent slopes is the most dominant and was selected for the simulation. It is a soil with a moderately high moisture, low organic matter but that responds well to lime and fertilizer. In that serie, the Loring silty clay 6 to 12 percent slopes eroded was also selected. Though sloppy and eroded, this soil is an important agricultural soil in the county. It is moderate in natural fertility and is strongly acid, but the response of crops to fertilizer and lime is good. In the Memphis-Wakeland series, the Memphis silt loam 2 to 6 percent slope is the most dominant. This is a deep well-drained soil with a high moisture supplying capacity. Natural fertility is moderate but crops respond well to lime and fertilizer on that soil of which most of the acreage is cultivated. The Wakeland 0-2% slope was also selected in that series. Finally, the Huntington 0-4%

slope was selected as the fifth soil in the model. For each soil, two series of yield data were obtained: irrigated and non-irrigated yield.

Appendix 4. Formulation of the Discrete Stochastic Sequential Programming Model

– Financial risk model

In order to present the mathematical model, notation is defined in this section.

Variables will be in upper case and parameters will be in lower case.

variables:

$\overline{NW_3}$	is the average expected net worth at the end of the period ($t=3$)
$ACRE_{E, D, S, P, F}$	is the number of acres produced for enterprise E on planting date D, soil S under production strategy P (“PA” for precision agriculture, “SDI” for subsurface drip irrigation, “WFM” for whole field management, and “D” for dry land) and fertilizer level F;
$CBAL_{t, i}$	is the cash balance for period t and state of nature i
$DEP_{t, i}$	is the total depreciation amount for periods t and state of nature i
$EASSET_{t, i}$	is the ending asset for period t for state of nature i
$EDEBT_{t, i}$	is the ending debt for period t for state of nature i
$IPA_{t, j}$	is the binary variable for the PA investment decision
$IPAI_{t, i}$	is the interest rate paid in period t and state of nature i
$IPURCH_{I, t, i}$	t is he purchase of inputs type I in period t and state of nature i
$ISDI_{t, i}$	is the total irrigation investment made in a given period i
$KPAID_{t, i}$	is the debt’s principal payment for period t and state of nature i
$LBOR_{t, i}$	is the long term capital borrowed in period t and state of nature i
$NR_{t, i}$	is the net return above variable cost for period t and state of nature i
$NW_{t, i}$	is the expected net worth for period t and state of nature i

- $SALES_{t,i}$ is the total farm sale for period t and state i (\$)
- $SBOR_{t,i}$ is the short term capital borrowed for period t and state of nature i
- indices:
- E represents the different enterprises (corn “C”, wheat “W”, and full season or double crop soybeans “B”)
- P is the production strategy and includes irrigation (SDI), variable rate application (VRA or PA), and whole field management (WFM).
- S represents the five soil types (Grenada, Huntington, Loring, Memphis, and Wakeland)
- F is the fertilizer application levels (very low, low, medium, high, and very high)
- D represents the planting dates for each crop
- I is the quantity of inputs applied on each soil
- t denotes the period in which a decision was made ($t=1, \dots, T$), where T is the end of the planning horizon;
- i is number of states of nature at time t
- j is number of states of nature at time $t-1$
- k is number of states of nature at time $t-1$ and $t-2$
- Y_r is the number of years

Coefficients and parameters:

- Φ is the Pratt risk-aversion coefficient
- IP_I is the inputs price by inputs type (I)
- P_E is the price of crop E in dollar per bushel including related costs

$ACRELIM_S$	is the total number of acres available to the farmer by soil type S
$YLD_{E,D,S,P,F,t}$	is the expected yield during year t for enterprise E at planting date D, under production strategy P, on soil type F (in bushels per acre)
$inputs_{I P F}$	is the inputs I required by production strategy and fertilizer level.
$sr_int_{t,i}$	is the short term interest rate for period t and state of nature i

Scalars include:

lr_int	is the long term interest rate for investment capital borrow
ic	is the per acre SDI equipment fixed cost
$invk_pa$	is the total capital amount invested in precision agriculture
$basset$	is the beginning asset value and is set at \$1,525,000
$bdebt$	is the beginning debt value and is set at \$499,000
$bcbal$	is the beginning cash balance value at \$129,254

Objective functions:

$$\text{Max } \overline{NW3} - \Phi \sigma_{NW}^2$$

Subject to constraints (1) to (19):

There are two types of constraints: production constraints (1) to (9), and accounting constraints (10) to (19).

$$(1a) \quad \sum_E \sum_P \sum_F \sum_D ACRE_{E,P,F,D,S,t,j} \leq acrelim_{S,t,j} \quad \forall S, t=1, \text{ and } j=1$$

$$(1b) \quad \sum_E \sum_P \sum_F \sum_D ACRE_{E,P,F,D,S,t,j} \leq acrelim_{S,t,j} \quad \forall S, t=2, \text{ and } j=1, \dots, 9$$

$$(1c) \quad \sum_E \sum_P \sum_F \sum_D ACRE_{E,P,F,D,S,t,k} \leq acrelim_{S,t,k} \quad \forall S, t=3, \text{ and } k=1, \dots, 81$$

$$(2a) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{inputs}_{I,P,F} * \text{ACRE}_{E,P,F,D,S,t,j} - \sum_I \text{IPURCH}_{I,t,j} \leq 0$$

$\forall S, t=1, \text{ and } j=1$

$$(2b) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{inputs}_{I,P,F} * \text{ACRE}_{E,P,F,D,S,t,j} - \sum_I \text{IPURCH}_{I,t,j} \leq 0$$

$\forall t=2 \text{ and } j=1, \dots, 9$

$$(2c) \quad \sum_E \sum_P \sum_F \sum_D \sum_S \text{inputs}_{I,P,F} * \text{ACRE}_{E,P,F,D,S,t,k} - \sum_I \text{IPURCH}_{I,t,k} \leq 0$$

$\forall t=3 \text{ and } k=1, \dots, 81$

$$(3a) \quad \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"W"}, P, F, D, S, t, j}$$

$$- \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"B"}, P, F, D, S, t, j} \leq 0 \quad \forall t=1 \text{ and } j=1$$

$$(3b) \quad \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"W"}, P, F, D, S, t, j}$$

$$- \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"B"}, P, F, D, S, t, j} \leq 0 \quad \forall t=2, \text{ and } j=1, \dots, 9$$

$$(3c) \quad \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"W"}, P, F, D, S, t, k}$$

$$- \sum_E \sum_P \sum_F \sum_S \text{SEQ}_{\text{"PS"}, \text{"PW"}} * \text{ACRE}_{\text{"B"}, P, F, D, S, t, k} \leq 0 \quad \forall t=3, \text{ and } k=1, \dots, 81$$

$$(4a) \quad \sum_P \sum_F \sum_D \sum_S \text{ACRES}_{\text{"C"}, P, F, D, S, t, j} - \text{ACRE}_{\text{"W"}, P, F, D, S, t, i}$$

$$- \text{ACRE}_{\text{"B"}, E, P, F, D, S, t, j} \leq 0 \quad \forall t=1 \text{ and } j=1$$

$$(4b) \quad \sum_P \sum_F \sum_D \sum_S \text{ACRES}_{\text{"C"}, P, F, D, S, t, j} - \text{ACRE}_{\text{"W"}, P, F, D, S, t, j}$$

$$- \text{ACRE}_{\text{"B"}, E, P, F, D, S, t, j} \leq 0 \quad \forall t=2, \text{ and } j=1, \dots, 9$$

$$(4c) \quad \sum_P \sum_F \sum_D \sum_S \text{ACRES}_{\text{"C"}, P, F, D, S, t, k} - \text{ACRE}_{\text{"W"}, P, F, D, S, t, k}$$

$$- \text{ACRE}_{\text{"B"}, E, P, F, D, S, t, k} \leq 0 \quad \forall t=3, \text{ and } k=1, \dots, 81$$

$$\begin{aligned}
(5a) \quad & \text{acrelim}_{S'} * \text{ACRE}_{E, P, F, D, S, t, j} - \text{acrelim}_{S, t, j} * \text{ACRE}_{E, P, F, D, S, t, j} = 0 \\
& \forall P = \text{WFM}, F, D, S \neq S', t=1, \text{ and } j=1 \\
(5b) \quad & \text{acrelim}_{S'} * \text{ACRE}_{E, P, F, D, S, t, j} - \text{acrelim}_S * \text{ACRE}_{E, P, F, D, S, t, j} = 0 \\
& \forall P = \text{WFM}, F, D, S \neq S', t=2, \text{ and } j=1, \dots, 9 \\
(5c) \quad & \text{acrelim}_{S'} * \text{ACRE}_{E, P, F, D, S, t, k} - \text{acrelim}_S * \text{ACRE}_{E, P, F, D, S, t, k} = 0 \\
& \forall P = \text{WFM}, F, D, S \neq S', t=3, \text{ and } k=1, \dots, 81 \\
(5'a) \quad & \text{acrelim}_{S'} * \sum_E \text{ACRE}_{D, P, F, S} - \text{acrelim}_S * \sum_E \text{ACRE}_{D, F, S', P} = 0 \\
& \forall P = \text{PA}, F, D, S \neq S' \\
(5'b) \quad & \text{acrelim}_{S'} * \sum_E \text{ACRE}_{D, P, F, S} - \text{acrelim}_S * \sum_E \text{ACRE}_{D, F, S', P} = 0 \\
& \forall P = \text{PA}, F, D, S \neq S' \\
(5'c) \quad & \text{acrelim}_{S'} * \sum_E \text{ACRE}_{D, P, F, S} - \text{acrelim}_S * \sum_E \text{ACRE}_{D, F, S', P} = 0 \\
& \forall P = \text{PA}, F, D, S \neq S' \\
(6a) \quad & \sum_E \sum_P \sum_F \sum_D \sum_S 1/\text{yr YLD}_{E, D, S, P, F} * \text{ACRE}_{E, P, F, D, S, t, i} - \text{SALES}_{t, i} \leq 0 \\
& \forall t=1 \text{ and } i=1 \\
(6b) \quad & \sum_E \sum_P \sum_F \sum_D \sum_S 1/\text{yr YLD}_{E, D, S, P, F} * \text{ACRE}_{E, P, F, D, S, t, j} - \text{SALES}_{t, j} \leq 0 \\
& \forall t=2, \text{ and } j=1, \dots, 9 \\
(6c) \quad & \sum_E \sum_P \sum_F \sum_D \sum_S 1/\text{yr YLD}_{E, D, S, P, F} * \text{ACRE}_{E, P, F, D, S, t, k} - \text{SALES}_{t, k} \leq 0 \\
& \forall t=3, \text{ and } k=1, \dots, 81 \\
(7a) \quad & \sum_E P_{C, t, i} * \text{SALES}_{E, t, i} - \sum_I IP_I * IPURCH_{I, t, i} - \text{NR}_{t, i} = 0 \quad \forall t=1 \text{ and } i=1 \\
(7b) \quad & \sum_E P_{C, t, i} * \text{SALES}_{E, j} - \sum_I IP_I * IPURCH_{I, t, j} - \text{NR}_{t, i, j} = 0 \\
& \forall t=2, i=1, \dots, 81, \text{ and } j=1, \dots, 9
\end{aligned}$$

$$(7c) \quad \sum_E P_{C,t,i} * SALES_{E,k} - \sum_I IP_1 * IPURCH_{I,k} - NR_{t,i,k} = 0$$

$\forall t=3, i=1,...,729, \text{ and } k=1,...,81$

$$(8a) \quad \sum_E \sum_S \sum_F \sum_D ACRE_{E,P,F,D,S,t,j} - IPA_{t,j} \leq 0 \quad \forall P=PA, t=2, \text{ and } j=1,...,9$$

$$(8b) \quad \sum_E \sum_S \sum_F \sum_D ACRE_{E,P,F,D,S,t,k} - IPA_{t,j} - IPA_{t,k} \leq 0$$

$\forall P=PA, t=3, j=1,...,9, \text{ and } k=1,...,81$

$$(9a) \quad \sum_E \sum_S \sum_F \sum_D ACRE_{E,P,F,D,S,t,i} * ic - ISDI_{t,i} - ISDI_{t,i} \leq 0$$

$\forall P=SDI, t=1 \text{ and } i=1$

$$(9b) \quad \sum_E \sum_S \sum_F \sum_D ACRE_{E,P,F,D,S,t,j} * IC - ISDI_{t,j} \leq 0$$

$\forall P=SDI, t=2, \text{ and } j=1,...,9$

$$(9c) \quad \sum_E \sum_S \sum_F \sum_D ACRE_{E,P,F,D,S,t,k} * IC - ISDI_{t,j} - ISDI_{t,k} \leq 0$$

$\forall P=SDI, t=3, j=1,...,9, \text{ and } k=1,...,81$

$$(10a) \quad EASSET_{t,i} - EDEBT_{t,i} - NW_{t,i} = 0 \quad \forall t=1, \text{ and } i=1,...,9$$

$$(10b) \quad EASSET_{t,i,j} - EDEBT_{t,i,j} - NW_{t,i,j} = 0 \quad \forall t=2, j=1,...,9, \text{ and } i=1,...,81$$

$$(10c) \quad EASSET_{t,i,k} - EDEBT_{t,i,k} - NW_{t,i,k} = 0 \quad \forall t=3, i=1,...,729, \text{ and } k=1,...,81$$

$$(11a) \quad \text{basset} - \text{bcash} + CBAL_{t,i} + LBOR_{t,i} - DEP_{t,i} - EASSET_{t,i} = 0$$

$\forall t=1, \text{ and } i=1,...,9$

$$(11b) \quad EASSET_{(t-1),j} + CBAL_{t,i,j} + LBOR_{t,i,j} - DEP_{t,i,j} - EASSET_{t,i,j} = 0$$

$\forall t=2, j=1,...,9, \text{ and } i=1,...,81$

$$(11c) \quad EASSET_{(t-1),k} + CBAL_{t,i,k} + LBOR_{t,i,k} - DEP_{t,i,k} - EASSET_{t,i,k} = 0$$

$\forall t=3, i=1,...,729, \text{ and } k=1,...,81$

$$(12a) \quad bdebt + LBOR_{t,i} + KPAID_{t,i} + SBOR_{t,i} - EDEBT_{t,i} = 0 \quad \forall t=1, \text{ and } i=1, \dots, 9$$

$$(12b) \quad EDEBT_{t-1,j} + LBOR_{t,i,j} + KPAID_{t,i,j} + SBOR_{t,i,j} - EDEBT_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(12c) \quad EDEBT_{t-1,k} + LBOR_{t,i,k} + KPAID_{t,i,k} + SBOR_{t,i,k} - EDEBT_{t,i,k} = 0$$

$$\forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81$$

$$(13a) \quad NR_{t,i} + bcbal - KPAID_{t,i} - IPAID_{t,i} - CBAL_{t,i} = 0 \quad \forall t=1, \text{ and } i=1, \dots, 9$$

$$(13b) \quad NR_{t,i,j} + CBAL_{t-1,j} - KPAID_{t,i,j} - IPAID_{t,i,j} - CBAL_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(13c) \quad NR_{t,i,k} + CBAL_{t-1,k} - KPAID_{t,i,k} - IPAID_{t,i,k} - CBAL_{t,i,k} = 0$$

$$\forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81$$

$$(14a) \quad \sum_I IP_1 IPURCH_{I,t,i} - bcash + min_cash - SBOR_{t,i} \leq 0 \quad \forall t=1, \text{ and } i=1, \dots, 9$$

$$(14b) \quad \sum_I IP_1 IPURCH_{I,t,j} - CBAL_{t-1,j} + min_cash - SBOR_{t,i,j} \leq 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(14c) \quad \sum_I IP_1 IPURCH_{I,t,k} - CBAL_{t-1,k} + min_cash - SBOR_{t,i,k} \leq 0$$

$$\forall t=3, i=1, \dots, 243, \text{ and } k=1, \dots, 81$$

$$(15a) \quad ISDI_{t,j} + IPA_{t,j} - LBOR_{t,i,j} = 0 \quad \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(15b) \quad ISDI_{t,k} + IPA_{t,k} - LBOR_{t,i,k} = 0 \quad \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81$$

$$(16a) \quad lti*(bdebt + LBOR_{t,i}) + sti_{t,i}*SBOR_{t,i} - IPAID_{t,i} = 0 \quad \forall t=1, \text{ and } i=1, \dots, 9$$

$$(16b) \quad lti*(LBOR_{t,i,j} + EDEBT_{t-1,j}) + sti_{t,i}*SBOR_{t,i,j} - IPAID_{t,i,j} = 0$$

$$\forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81$$

$$(16c) \quad lti*(LBOR_{t,i,k} + EDEBT_{t-1,k}) + sti_{t,i}*SBOR_{t,i,k} - IPAID_{t,i,k} = 0$$

$$\begin{aligned}
& \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81 \\
(17a) \quad & (bdebt/20) - KPAID_{t,i} = 0 \quad \forall t=1, \text{ and } i=1, \dots, 9 \\
(17b) \quad & (bdebt/20) + (ISDI_{t,j}/10) + (IPA_{t,j})/5 + KPAID_{(t-1)j} - KPAID_{t,i,j} = 0 \\
& \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81 \\
(17c) \quad & (bdebt/20) + (ISDI_{t,k}/10) + (IPA_{t,k})/5 + KPAID_{(t-1)k} - KPAID_{t,i,k} = 0 \\
& \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81 \\
(18a) \quad & (ISDI_{t,j}/10) + (IPA_{t,j}/5) + DEP_{(t-1)i} - DEP_{t,i,j} = 0 \quad \forall t=2, j=1, \dots, 9, \text{ and } i=1, \dots, 81 \\
(18b) \quad & (ISDI_{t,k}/10) + (IPA_{t,k}/5) + DEP_{(t-1)k} - DEP_{t,i,k} = 0 \\
& \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81 \\
(19) \quad & \overline{NW3} = \alpha_{Ti} (1/i*k) * NW3_{t,i,k} \quad \forall t=3, i=1, \dots, 729, \text{ and } k=1, \dots, 81
\end{aligned}$$

Constraints description

- (1a,b&c) land resource availability constraint respectively for periods 1, 2, and 3
- (2a,b&c) inputs purchase balance by inputs type respectively for periods 1, 2, and 3
- (3a,b&c) soybeans and wheat planting schedule respectively for periods 1, 2, and 3
- (4a,b&c) crop rotation constraints respectively for period 1, 2, and 3
- (5a,b&c) ratio constraint to control for non-variable rate management strategy under WFM or uniform rate fertilizer application respectively for periods 1, 2, and 3
- (5'a,b&c) ratio constraint to control for non-variable rate management strategy under PA or variable rate fertilizer application respectively for periods 1, 2, and 3
- (6a,b&c) sales balance respectively for periods 1, 2, and 3

- (7a,b&c) profit balance respectively for periods 1, 2, and 3
- (8a,b&c) precision agriculture investment constraint f respectively or periods 1, 2,
and 3
- (9a,b&c) subsurface drip irrigation (SDI) investment constraint respectively for
periods 1, 2 ,and 3
- (10a,b&c) expected ending net worth respectively for periods 1, 2, and 3
- (11a,b&c) ending asset respectively for periods 1, 2, and 3
- (12a,b&c) ending debt respectively for periods 1, 2, and 3
- (13a,b&c) cash balance constraint respectively for periods 1, 2, and 3
- (14a,b&c) short term borrowing respectively for periods 1, 2, and 3
- (15a,b&c) long term borrowing respectively for periods 1, 2, and 3
- (16a,b&c) interest paid on borrowing respectively for periods 1, 2, and 3
- (17a,b&c) reimbursement of the debt principal respectively for periods 1, 2, and 3
- (18 a,b&c) total investment depreciation respectively for periods 1, 2, and 3
- (19 a,b&c) objective function constraint respectively for periods 1, 2, and 3

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- Jean-Marc Gandonou and Carl R. Dillon "The Potential of Precision Agriculture in a Developing Country: Cotton in Benin". Paper selected for the 7th International Conference on Precision Agriculture, Minneapolis, MN. July 25-27, 2004.

- Jean-Marc Gandonou and Carl R. Dillon. “Precision Agriculture, Whole Field Farming and Irrigation Practices: A Financial Risk Analysis”. Paper selected for the American Agricultural Economics Association (AAEA) meeting, Montreal, Canada, July 27-30, 2003.
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